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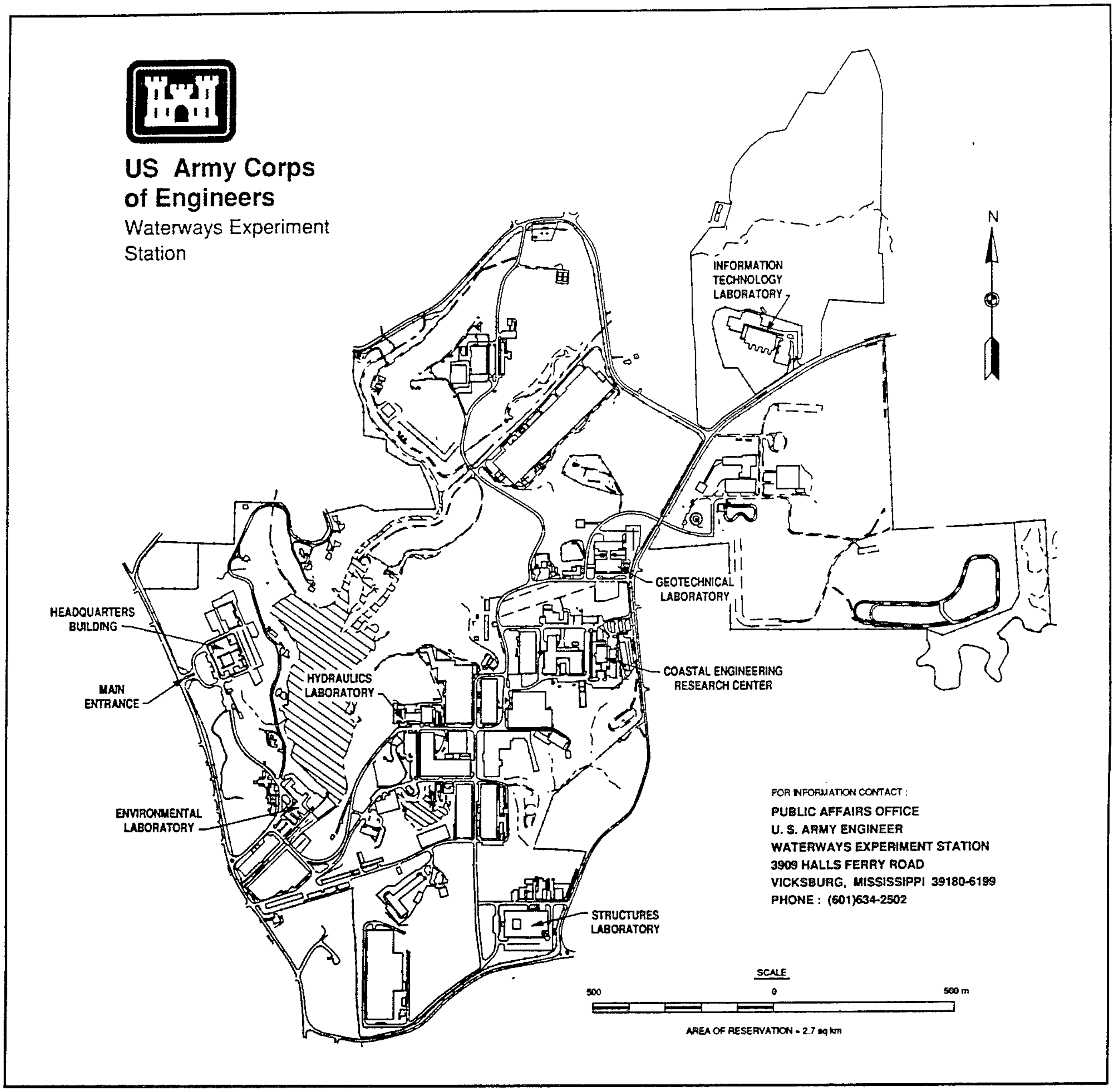
State-of-the-Art for Assessing Earthquake Hazards in the United States

Report 29
Selection of Earthquake Ground Motions for Engineering

by E. L. Krinitzsky

Prepared for Headquarters, U.S. Army Corps of Engineers



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Preface

This report was sponsored by the Department of the Army and is part of ongoing Civil Works studies in Earthquake Engineering: Geological - Seismological Evaluation of Eqrthquakes.

The preparation and writing of this report was by Dr. E. L. Krinitzsky, of the Geotechnical Laboratory (GL), U.S. Army Engineer Waterways Experiment Station (WES). Dr. Mary Ellen Hynes was the author of Appendix E.

At the time of publication of this report, Dr. W. F. Marcuson, III was Director of GL. The Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard.

Chapter 1
Introduction

1-1. Background

a. Until the early 1970s, earthquake design criteria for Corps of Engineers civil structures consisted of the application of equivalent lateral static forces to be resisted by the designed structural system. These equivalent lateral static forces, termed "seismic coefficients," were generally based upon seismic risk maps produced by the Uniform Building Code or the Applied Technology Council. The seismological studies performed during feasibility and design studies consisted of cataloging historical earthquakes and their intensities in the region of the planned project. In seismically active areas, such as California, precautions were taken to avoid siting structures on active faults. There were no criteria for determining fault activity.

b. The Niigata, Japan, earthquake of 1963 and the Alaskan earthquake of 1964 were instrumental in developing increased awareness of seismic hazards from severe shaking, soil liquefaction, and permanent deformation in foundations. The initiation of nuclear power plant construction in the 1960s and the awareness of the hazards of siting such critical facilities in seismically active areas resulted in the formal Federal promulgation of criteria for the determination of earthquake hazards and earthquake resistant design. The near failure of the Lower San Fernando Dam as the result of the San Fernando, California, earthquake of 1971 resulted in an extensive effort on the part of the Corps of Engineers and other agencies responsible for the construction of major structures to take steps to ensure that existing and future projects remain safe in the event of earthquakes. Research and development activities were undertaken to produce criteria for safe design and evaluation. Engineer guidance was promulgated periodically to provide the Corps' field activities with the developing criteria and appropriate methods.

1-2. Scope

a. The procedures presented in this report are intended to allow geology and engineering personnel in the Corps' field activities to determine the appropriate design earthquake or earthquakes for any project or site and to select analogous free field ground motions appropriate for the site. The earthquakes and ground motions will be acceptable unless their application to design analyses produces borderline results (e.g. economically unacceptable design results or the project appears to be not feasible). Because the state of the art in engineering seismicity and in earthquake design is still evolving, borderline results will require further detailed studies, performed by recognized experts in the field. In such a case, the procedures in this manual will facilitate the focussing of such detailed studies by others.

b. Chapter 2 introduces the reader to definitions and concepts in engineering seismology and to the deterministic and probabilistic methods of seismic hazard evaluations. Chapter 3 reviews seismological inputs to evaluations and Chapter 4 provides guidance on geological assessments. Chapter 5 reviews map sources and their appropriateness for applications at engineering sites. Chapter 6 considers general principles for assigning earthquake ground motions and Chapter 7 provides recommended methods for specifying earthquake ground motions that are both site specific and appropriate for the types of engineering analyses in which they are to be used. Appendixes present references, magnitude-based charts for ground motions with recommended accelerograms, intensity-based charts for ground motions with recommended accelerograms, and a description of probabilistic seismic hazard analysis. A Glossary is included defining the terms used in this manual.

c. The general process involved in the earthquake analysis of a structure consists of the following steps:

(1) Decision on the need for an earthquake analysis.

(2) Evaluation of geological and seismological factors to consider in the formulation of design earthquakes.

(3) Selection of design earthquakes and development of site-specific earthquake ground motions for engineering analyses.

(4) Performance as needed of dynamic or pseudostatic analyses.

(5) Evaluation of structural adequacy for earthquake loading.

d. Of the above-listed steps, the first step is controlled by Corps policy. General guidelines for determining the need for earthquake analyses are contained in appropriate Engineer Regulations such as ER 1110-2-1806. The fourth and fifth steps are beyond the purview of this report. The intervening steps two and three are the essence of this report.

Chapter 2
Concepts and Definitions

2-1. Causes of Earthquakes

a. The causes of earthquake vibratory ground motion include:

(1) Impact of extraterrestrial bodies.

(2) Large man-made explosions on or below the earth's surface.

(3) Mineralogical phase changes deep within the earth. Volcanic eruptions at or near the earth's surface.

(4) Abrupt rupture along faults.

b. Of the above, extraterrestrial impacts can be ignored as too rare, man-made explosions must be examined on the individual characteristics, mineralogical phase changes occur at depths too great to affect engineering, and volcanic eruptions cause ground shaking only by breaking the brittle crust through fault ruptures. Thus rupture on faults can be regarded as the only cause for earthquakes.

c. The principle underlying the production of earthquakes by fault movement is termed *elastic rebound.* Strain energy builds up in the rocks of the earth's crust as a result of tectonic stresses. A sudden rupture relieves all or part of the built-up stresses and produces the earthquake vibratory ground motions.

d. Plate tectonics provides an explanation for the occurrence and distribution of earthquake-producing faults. Crustal plates are pulling apart from each other, they override each other, and they slide past each other. The western plate boundary for North America is along the west coast of the continent between the American Plate and the Pacific Plate. The North American Plate is overriding the Pacific Plate and the latter is being absorbed in a deep subduction zone that extends more than 100 km below the surface. In California, the subduction zone is believed to have been consumed and the boundary consists of transform, laterally slipping faults. The San Andreas fault is one of these transform faults. The subduction zone has shallow earthquakes with focal depths to ~70 km; the brittle crust elsewhere has earthquakes with focal depths to ~20 km.

e. In the western interior of the United States, subplates have formed in response to subcrustal convective flow. Earthquakes occurring within plates are termed intraplate earthquakes. These intraplate earthquakes can be as severe as those along plate boundaries; however, they are much less frequent.

f. In the eastern United States, earthquakes in the Mississippi Valley are due to continuing activity at the northern end of the Mississippi embayment, in a structural trough that dates to the Paleozoic and which is still downwarping. The New Madrid fault zone, source of the very large 1811-1812 earthquakes, is located in a rift zone within this trough.

g. Elsewhere in eastern United States there are earthquake-generating hotspots at Charleston, South Carolina, Giles County, Virginia, and Cape Ann, Massachusetts. Also there is an area of seismicity in southeastern Illinois and southwest Indiana, the Wabash source zone, which may be an extension of the New Madrid zone. Another source is in the St. Lawrence Valley with extension into northernmost New York state.

h. The earthquake sources noted above are discussed in Chapter 3.

2-2. Movements on Faults

Following are basic concepts concerning fault movements.

a. Faults are either *active* or *inactive*. There are faults everywhere. The overwhelming majority of faults are the result of past tectonism, upheavals of the earth that occurred in earlier geological time. Such faults are usually dead. Faults produced by past tectonism can be activated today by present-day tectonism. But there must be some evidence of this reactivation, either in the geomorphology or the seismicity. Past tectonism alone cannot serve as a clue for interpreting modern fault activity.

b. Many faults are active but do not produce earthquakes. Such faults have movement, but there is an insufficient stress drop so that the movement takes place as creep. The cause may be shallowness, resulting in a dissipation of stresses or there may be soft materials in the fault plane that deform plastically. Also, there may be a lack of friction, or asperities, or barriers along a fault, thus allowing small but steady energy releases. Such conditions prevail where:

(1) Growing salt domes activate small shallow faults in soft sediments.

(2) Extraction of fluids (oil or water), or lowering of a water table by natural processes, causes ground settlement and the activation of faults in the zone undergoing adjustment.

(3) Tectonically activated faults become adjusted by a steady creep.

(4) Gravity slides take place in thick, unconsolidated sediments. Such slides are rootless faults, ones that do not reach crystalline basement rocks where stress drops can be appreciable. They behave like enormous landslides. Thus, there are active faults that do not produce earthquakes and there are active faults that do. The latter are called *capable faults*, meaning that they are capable of producing earthquakes.

c. Active faults need to extend into crystalline basement rocks if they are to build up the strain energy needed to produce earthquakes strong enough to affect engineered structures. Focal depths of 7 to 20 km seen in microearthquakes ($M \leq 3.5$) are clues to potentially large earthquakes ($M = 6.0$ or greater). Microearthquakes at focal depths of 1 to 3 km, that commonly occur where reservoirs are impounded, are not suitable as evidence for possible $M = 6.0$ events. One may take $M = 6.0$ as the threshold of a severity that can begin to damage well engineered structures.

d. Existing faults are sufficient to accommodate all interpreted earthquakes. To require the production of totally new faults during an earthquake is unwarranted.

e. Fault ruptures commonly occur in the deep subsurface with no ground breakage at the surface. Such behavior is widespread, accounting for almost all earthquakes in central and eastern United States. They account also for significant earthquakes in the plate boundary areas.

f. Whether or not a fault will produce earthquakes can be judged by the recency of previous movements. The evidence is in geomorphic features considered with rootedness of the fault and the geomorphic evidence from previous earthquakes. If a fault moved a geologically short time ago (Holocene and/or Pleistocene), it has the potential to move again. If it moved in the distant geologic past (Pre-Pleistocene) and has not moved again since then, it may be judged to be a dead fault.

g. Geomorphic evidence of fault movement is not always datable. In practice, if a fault cuts the base of alluvium, the base of glacial deposits, or cuts surficial gravels, then the fault is regarded as active. If there is also recent seismicity, the fault can be judged as capable of generating earthquakes. If there has been no seismicity, then the fault, though active, may not be one that is capable of generating earthquakes.

h. The size of a potential maximum earthquake, on a capable fault, is relatable to the size of the fault. A small fault produces small earthquakes; a large fault produces large earthquakes. There is no reason to expect a 1906 San Francisco earthquake in Florida because there is no San Andreas fault in Florida and no large area of intense microearthquake activity.

i. Very large and capable faults do not produce all sizes of earthquakes. Faults contain asperities or are subject to certain frictional restraints that allow them to move only when certain levels of stresses are achieved. However, asperities wear out and change through time. The maximum potentiality can be judged from the dimensions of the largest previous fault ruptures.

j. A long fault, like the San Andreas in California or the Wasatch in Utah, does not move along its entire length at any one time. The fault moves in portions, a segment at a time. An unmoved segment, where all other segments have moved, is a candidate for the next movement. Segment dimensions, however, need not be the same through time.

k. Short, disconnected faults, often *en echelon*, forming a fault zone, are probably connected at depth but their surface expression may have been modified by overlying deposits. The observed length of groups of such faults often is shorter than their true length. The true length may be seen in the extent of microearthquakes following a major earthquake. The widths of these fault zones is proportional to the fault lengths.

l. It is not likely that all faults will be found. Evaluations and later design decisions should be made in such a way that results are relatively insensitive to later identification of faults that were not found. Floating earthquakes in interpreted earthquake zones can be an appropriate solution.

2-3. Criticality of Seismic Evidence

The best evidence that identifies present-day tectonism is seismicity. The historic records of earthquakes, even in the areas of the United States where the periods of record are short, are the most reliable indicators of present-day seismic hazards. The historic record can be extended by evidence from paleoseismicity. The seismic evidence is measured by scales of earthquake intensity and of magnitude.

2-4. Earthquake Intensity

a. The Modified Mercalli (MM) intensity scale of 1931 is the intensity scale used in the United States. The Glossary contains an abridged version by Wood and Neumann (1931). The scale is discussed more extensively by Richter (1958) and Barosh (1969).

b. Figure 2-1 compares the MM scales of the Japanese Meteorological Agency (Okamoto 1973), the Peoples Republic of China (Hsieh 1957), Rossi-Forel (see Richter 1958), and Medvedev, Sponheuer, and Karnik (Medvedev and Sponheuer 1969).

c. The oldest of the above-mentioned scales is Rossi-Forel which dates to 1883. Mercalli in 1902 devised a scale with 10 grades, then developed it to 12 grades. The improvements were in better scaling of the effects from severe earthquake shaking. Sieberg in 1923 developed a version of the Mercalli scale that was revised by Wood and Neumann (1931) producing the MM scale of today. The Medvedev, Sponheuer, and Karnik scale, used in the former Soviet Union and east European countries, is a slight modification of the MM. The Chinese scale is identical to MM.

d. The Japanese scale is the only one used today that differs appreciably from the MM. Okamoto (1973) gives the following equation to relate the Japanese scale to MM:

$$I_{MM} = 0.5 + 1.5\ I_{JMA} \tag{2-1}$$

e. In the Glossary, intensity is seen to be principally a measure of damage especially in the upper registers of damage. A detail that is out-of-date in this description is the criterion of soil liquefaction which is now known to occur over a larger range of intensity levels beginning at MM VII.

f. Though intensity scales measure damage, not every site with a potential intensity level will experience

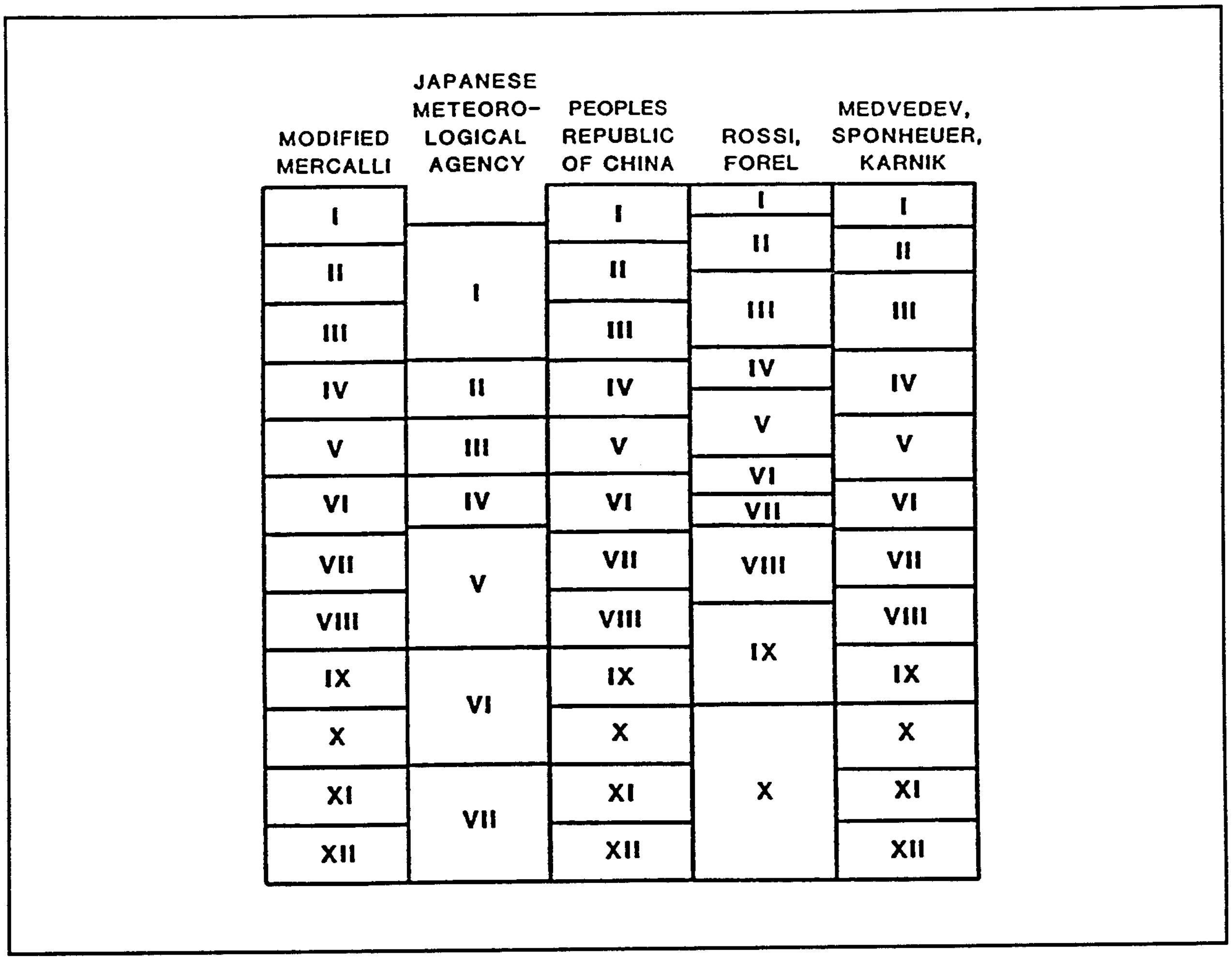


Figure 2-1. Comparison of intensity scales

the same damage since there are many vagaries in earthquake shaking and there may not be susceptible structures present. The intensity levels are a measure of potentials for damage.

2-5. Earthquake Magnitude

a. The definitions for earthquake magnitudes in Appendix B show them to be mostly indirect estimations of strain energy as measured in displacement amplitudes of seismic waves of certain periods and at certain distances from sources. Moment magnitude is a more direct measure of energy since it is based on calculated frictional resistance over the area of fault slippage. The advantage of the moment scale is that it provides values for extremely large earthquakes beyond where the other scales have saturated. The disadvantage is that the friction must be estimated and can be highly variable. However, the moment scale will not help in specifying earthquake ground motions more accurately because the seismograph records of the peak motions (acceleration, velocity, etc.) will themselves have been saturated.

b. A number of magnitude scales are in use, six of which are described in Appendix E: body wave magnitude (m_b), local magnitude (M_L), surface wave magnitude (M_S), Richter magnitude (M), seismic moment (M_o), and the seismic moment scale (M_w).

c. Magnitude scales differ somewhat between a plate boundary source area and that of an intraplate. Table 2-1 shows comparisons of the above magnitude scales with equivalent MM intensities for plate boundary and intraplate areas.

2-6. Earthquake Ground Motions

a. An earthquake is a complex series of vibratory ground motions which emanate from a source of disturbance in the brittle zone of the earth's crust. These motions take the form of body waves which propagate in the interior of the earth and surface waves which propagate along or near the surface of the earth. Body waves are composed of compressional and shear waves and surface waves are composed of Rayleigh and Love waves. Definitions of these waves are contained in the Glossary.

(1) Ground motion is generally strongest in the vicinity of its source (near, or at, the fault rupture), with the severity of shaking diminishing with distance.

(2) The predominant periods of ground motion vibration generally trend toward longer periods as distance increases from the source. This is due to the attenuation of the higher frequency content of the wave train and spreading of the waves.

(3) Deep deposits of soft soils tend to produce ground surface motions having predominantly long period characteristics and may greatly accentuate peak motions and their durations.

Table 2-1
Equivalences Between Magnitude Scales and Intensity (Magnitudes were modified from Nuttli and Shieh (1987))

Plate Boundary

M	m_b	M_L	M_S	M_W	M_o (dyne-cm)	Epicentral Intensity MM
4.3	4.0	4.3	3.0	4.1	10^{21}	IV
4.8	4.5	4.8	3.6	4.5	10^{22}	V
5.3	5.0	5.3	4.6	5.2	10^{23}	VI
5.8	5.5	5.8	5.6	5.8	10^{24}	VII
6.6	6.0	6.3	6.6	6.6	10^{25}	VIII
7.3	6.5	6.8	7.3	7.3	10^{26}	IX-X
8.2	7.0	7.3	8.2	8.2	10^{27}	XI-XII

Plate Interior

M	m_b	M_L*	M_S	M_W	M_o (dyne-cm)	Epicentral Intensity MM
4.3	4.0	-	2.9	3.8	10^{21}	IV
4.8	4.5	-	3.4	4.1	10^{22}	V
5.1	5.0	-	4.4	4.8	10^{23}	VI
5.4	5.5	-	5.4	5.4	10^{24}	VII
6.4	6.0	-	6.4	6.1	10^{25}	VIII
7.4	6.5	-	7.4	6.8	10^{26}	IX-X
8.4	7.0	-	8.4	7.4	10^{27}	XI-XII

* M_L generally not used in plate interior.

(4) Deposits of stiff soils or rock result in ground motions having predominantly short period characteristics compared to softer materials.

b. The basic measurement of earthquake ground motion of engineering interest is the accelerogram record taken by special strong motion seismometers. The strong motion accelerogram is popularly called the earthquake's "time history." These records form a primary database for seismic load specifications. A typical seismometer station provides records of two orthogonal horizontal components of motion and one vertical. For a single component, the time derivative relations between ground displacement, velocity, and acceleration allow the presentation of each of these motion histories, as shown in Figure 2-2. The maximum of peak values of displacement (PGD), velocity (PGV), and acceleration (PGA) provide the most elementary and popular measures of an earthquake's severity. Duration or "bracketed" duration of strong motion is also an important measure.

c. While accelerograms are necessary for some earthquake analyses, others can employ more engineering-related characterizations of ground motion. A widely used representation with utility in structural response analysis (modal analysis) is the response spectrum. This spectrum can be used not only to describe the intensity and vibration frequency content of accelerograms at various levels of structural damping, but has an important advantage in that spectra from several earthquake records can be normalized, averaged, and then scaled to predict future motion at a given site. A schematic representation of how an acceleration response spectral diagram is created is shown in Figure 2-3. A set of linear elastic single degree of freedom systems having a common damping ratio, but each having different harmonic periods over a range of times, is subjected to a given ground motion accelerogram. The entire time history of acceleration response is found for each system and the corresponding value of spectral acceleration is plotted on the period axis. The curve connecting these spectral-acceleration values is

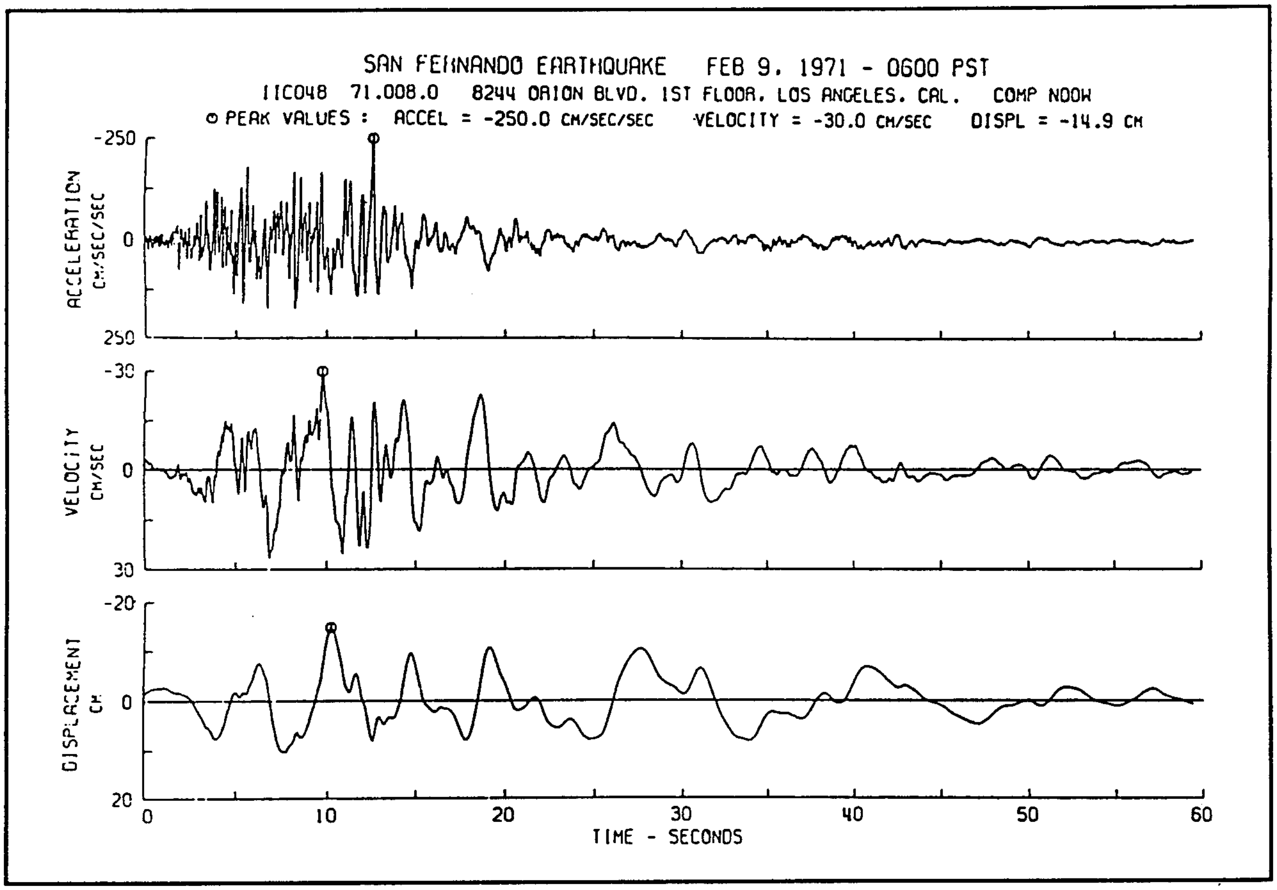


Figure 2-2. Processed record for one direction of horizontal strong motion

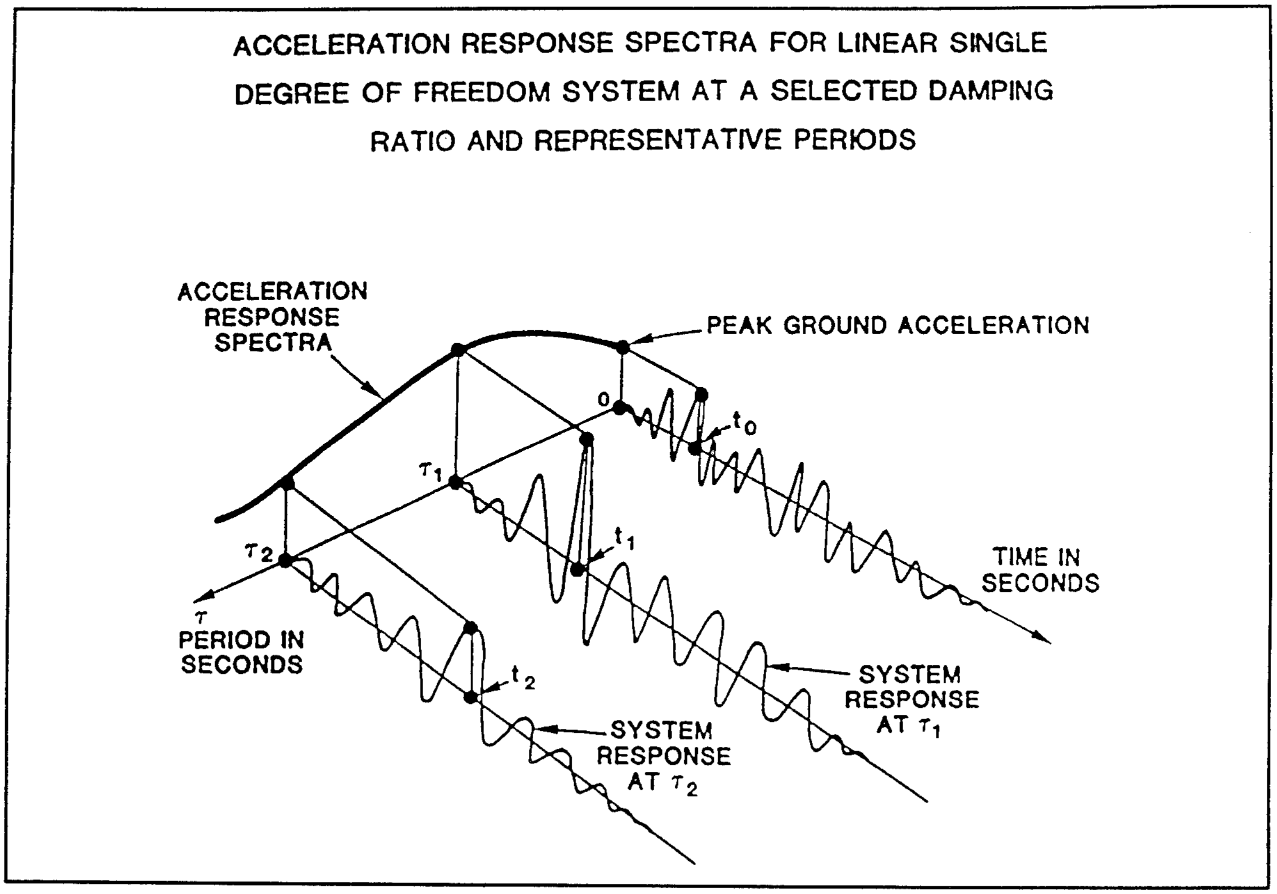


Figure 2-3. Schematic representation of how an acceleration response spectral diagram in created

the acceleration response spectrum for the given acceleration and damping ratio. Actual spectra are shown in Figure 2-4. Response values also may be calculated as a function of the natural period by assuming the motions are harmonic and undamped. These are referred to as pseudo-acceleration, pseudo-velocity, and pseudo-displacement response spectrum values.

d. Seismic waves traveling from rock at depth through surficial deposits to the surface will be modified as a function of the amplitude of the seismic motion, and the depth, structure, and dynamic properties of the soils. The inclination of the soil layers and the bedrock surface can influence reflection and refraction of the seismic waves and consequently their complexity.

Surface topography also affects the ground motion in that peaks or jutting outcrops may change the seismic motions. Calculating these site effects is generally performed as part of the structural dynamic analyses. For this reason the motions supplied are given as free field motions at the ground surface for rock and/or soil.

2-7. Deterministic and Probabilistic Procedures

a. The deterministic method for evaluating seismic hazard uses all available geological and seismological information and assigns motions by a combination of empirical knowledge, theoretical conceptualization, and professional judgment. The motions are not time dependent, meaning they are independent of the interval of recurrence for the motions, or their probability. A probabilistic seismic hazard analysis is a quantitative estimate that a certain level of site ground motion will be exceeded in a specified time period.

b. Problems with the probabilistic method are discussed by Krinitzsky (1993). Essentially the difficulty is that fault mechanisms for generating earthquakes involve (1) *stick slip*, (2) *controlled slip*, and (3) *thermodynamic slip*. Stick slip relates well to b-lines described in the Glossary, controlled slip does not, and thermodynamic slip deviates powerfully from b-lines. Thermodynamic slip affects the larger earthquakes ($M \geq 6$) that are of the greatest concern in engineering. The applicability or

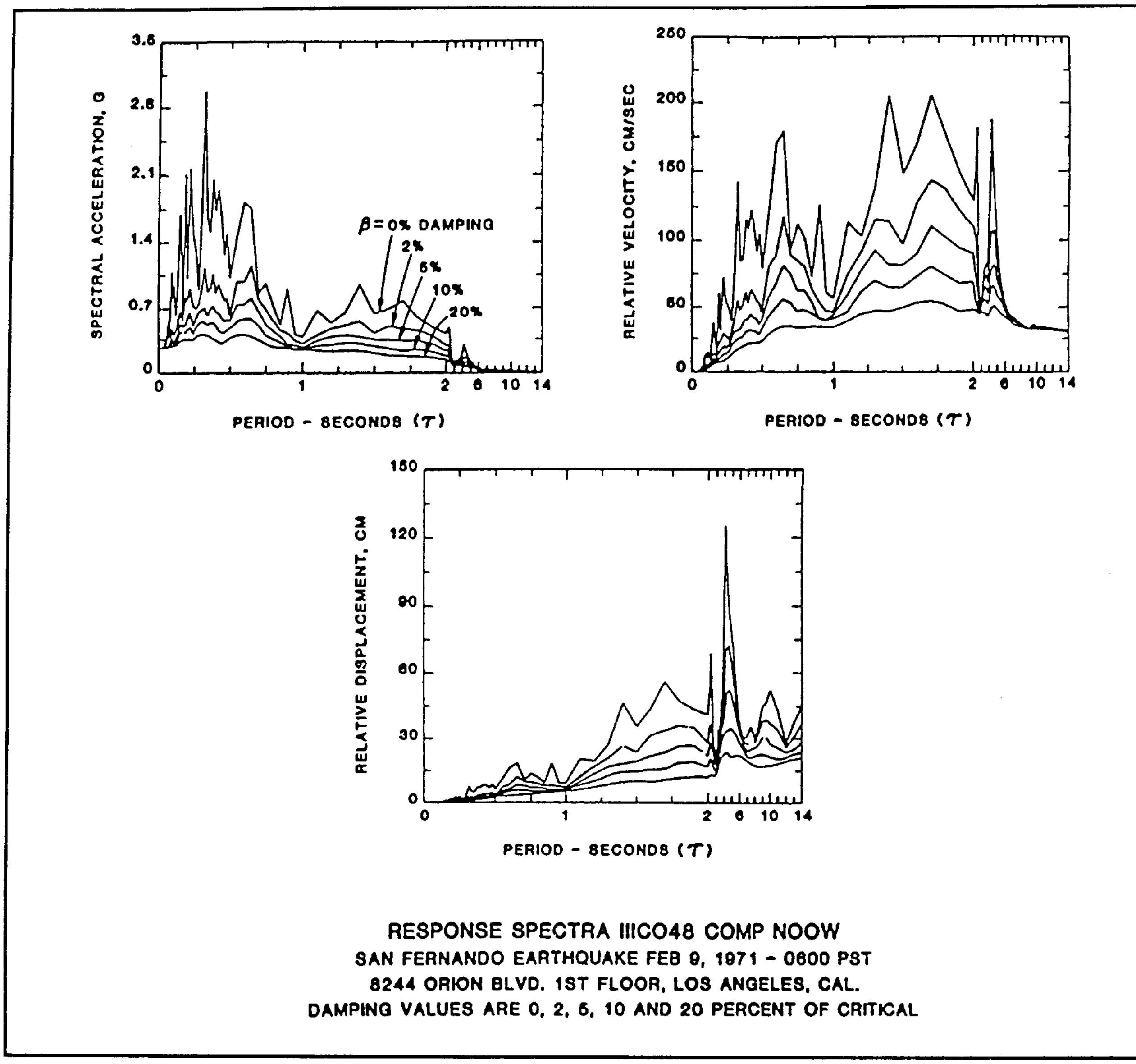


Figure 2-4. Spectral acceleration, relative velocity, and relative displacement for 0, 2, 5, 10, and 20 percent damping

nonapplicability of the b-line is crucial since its use for predicting time-dependent recurrences of earthquakes makes it the heart of the seismic probability method.

c. This manual requires that deterministic procedures be used to obtain maximum credible earthquakes for critical structures in seismically active areas. For all other categories of analysis, either deterministic or probabilistic methods may be used.

2-8. Terminology for Engineering

a. The Glossary contains a number of differing terms that have identical meanings, such as *maximum credible earthquake* and *maximum expectable earthquake*, or terms that have limited differences, such as *maximum credible earthquake* and *safe shutdown earthquake*, the latter being the same as the former except that the definition applies to nuclear reactors only. Terms such as *investment protection earthquake*, where *operating basis earthquake* is meant, have come about where engineers have sought special nuances of meaning, or euphemisms, in relation to their projects. These are effects of usage and the language is constantly changing.

b. Some definitions are becoming outdated and others can easily be misapplied. A *capable fault* is one that moved within the last 35,000 years. But why 35,000 years? That was approximately the ±2 percent accuracy level that existed some years back on reliability for Carbon-14 dating for good samples of organic matter. Today that range can be extended to 70,000 to 90,000 years by enrichment techniques. But the definition remains at 35,000 years because it is a published criterion of the Nuclear Regulatory Commission. Another NRC criterion is that a capable fault shows recurrent movement during the past 500,000 years. The 500,000 years was originally related to the ages of marine terraces along the California coast. This criterion, when it was generated, was mostly meaningless beyond the coastline of California. It is still meaningless though today Uranium-series tests on bones and carbonates can be performed to 600,000 years but the tests are highly uncertain because of a problem in the lack of a closed system for the carbonates. Obviously, judgment is needed to make use of the definitions.

c. Where there are several definitions, the Glossary gives a "Recommended Definition."

2-9. Earthquake Distance for Engineering

Approximations of distances over which earthquakes can affect engineered structures are given in Table 2-2. For the majority of earthquakes, the distances of concern are relatively small. Seismic wave amplification in soft soils (Mexico City, and the San Francisco Bay area) is an exception as is soil liquefaction potential from a great earthquake.

Table 2-2
Approximations of Maximum Distances from Earthquake Sources that are Meaningful for Engineering. From Krinitzsky (1993)

Construction and Site Susceptibility	Threshold of Damage at Site, Mean Acceleration g	Earthquake at Fault Source		Maximum Distance, Plate Boundary Earthquake, Fault Source to Site km
		Magnitude M	Intensity MM I_0	
All major structures on stable foundations, M ≥ 6.0	0.15	6.0	VIII	20
		7.0	X	32
		8.0	XI	50*
Soil liquefaction (with permanent ground movement) M ≥ 5.3	0.10	5.3	VII	1
		6.0	VIII	10
		7.0	X	50
		8.0	XI	150
Seismic wave amplification in a shallow basin with soft soil M ≥ 7.0	0.5	7.0	X	230
		8.0	XI	400

* = 150 km for an intraplate event.

Chapter 3
Seismological Evaluation

3-1. Objectives

a. A seismological study evaluates

(1) Source areas for earthquake activity, including special emphasis on the possible activity of faults at the project site.

(2) Mechanisms by which these earthquakes are generated.

(3) Patterns of recurrence.

(4) Attenuations for earthquake ground motions.

b. In combination with the geological study, which should be run concurrently, the combined studies serve to specify the maximum credible earthquakes that are appropriate for each seismic source.

3-2. Data Sources

a. The National Geophysical Data Center/World Data Center, in Boulder, Colorado, maintains a computerized earthquake database for source data plus a file of earthquake strong motion records, both with worldwide coverage. Their data are available for purchase. The data center is also a source for geophysical data that include magnetic and gravity surveys, geothermal information, records of tsunamis, volcanic activity, seismic reflection and refraction profiles, etc. These materials are valuable as background information for interpretations of the earthquake information. Current information on major earthquakes happening in the United States or in the world can be obtained by calling the National Earthquake Information Center, also located in Boulder, Colorado. In addition, the National Geophysical Data Center maintains a database of worldwide strong motion accelerograph records and response spectra.

b. Universities and public agencies generate data from local and regional seismic arrays and they perform special studies of these data. For older earthquakes, it may be useful to check contemporary newspaper accounts and related historical information. Often the intensity levels need to be reinterpreted and the epicentral locations may be subject to change.

c. Attenuations of earthquake ground motions differ dramatically between plate boundary and intraplate areas. Attenuations also differ locally within those areas. A chart for attenuations of MM intensities over the United States was provided by Chandra (1979) and is illustrated in Figure 3-1. An appropriate curve will serve to adjust a maximum MM intensity value from a source area over a distance to a site. The curves are generalizations from variables that occur in the propagation of earthquake effects in different directions.

d. Adaptation of western United States motions (acceleration for magnitude and distance from source) for application in eastern United States is illustrated in Figure 3-2. The figure is from the procedure used by Algermissen et al. (1982). A similar construction was used by those authors for velocity. There are sets of curves that relate earthquake ground motions with magnitude and distance from source and for intensity. These will be discussed later in sections dealing with the specification of earthquake ground motions.

3-3. Locating Potential Earthquakes

a. Seismic history can be interpreted to form zones of seismicity. A seismic zone is an inclusive area over which an earthquake of a given maximum magnitude is postulated to occur anywhere. The earthquake is a *floating earthquake.* A seismic zone is supplemental to, and can include, the causative faults that have been identified as sources of earthquakes. The use of zones with floating earthquakes provides compensation for the possibility of capable faults that have not been mapped.

b. Seismic zones usually do not coincide with tectonic or physiographic provinces. The latter were formed by past tectonism. The seismic zone is the tectonism of the present. Its basis is in observed earthquakes. Thus seismic zones are determined by the patterns of earthquakes and the maximum sizes are guided by the sizes of observed earthquakes.

c. Criteria for shaping seismic zones are:

(1) Zones that have great activity should be as small as possible. They are likely to be caused by a definite structure, such as a fault zone or a pluton, and activity should be limited to that structural association. Such a source may be a *seismic hotspot.* A seismic hotspot requires one or more large historic earthquakes, frequent to continuous microearthquakes, and a well defined area. Maps of residual values for magnetometer and Bouguer gravity surveys may provide structural information to corroborate the boundaries of hotspots.

(2) One felt earthquake can adjust a boundary to a seismic zone but cannot create a zone.

(3) The maximum felt earthquake is equal to or less than the maximum zone earthquake.

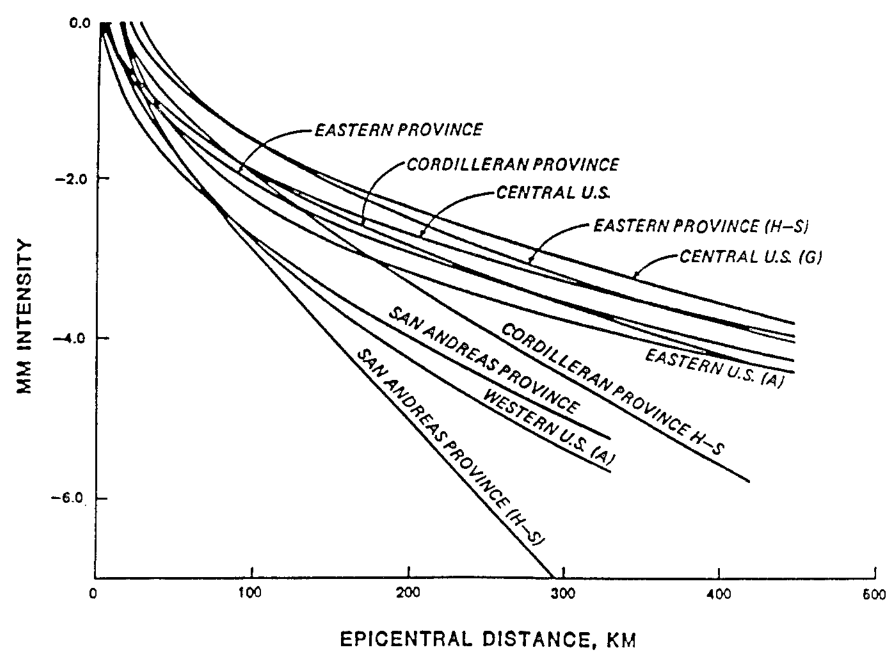


Figure 3-1. Change in the MM Intensity with distance for various areas of the United States. A = Anderson; G = Gupta; H-S = Howell- Schultz. See Chandra (1979)

(4) The maximum zone earthquake is a floating earthquake, one that can occur anywhere in that zone.

(5) Assignment of the maximum zone earthquake is judgmental.

d. Figure 3-3 shows seismic zones with Modified Mercalli intensity values for floating earthquakes. These zones are for Puerto Rico, Alaska, and the United States east of the Rocky Mountain Front. They were developed by Krinitzsky, Gould, and Edinger (1993) using the criteria cited above. Western United States is shown as a region of capable faults. Evaluations must be based on studies of faults near the construction site being investigated. Additionally, there is a subduction zone beginning in northern California and extending along the Pacific coast to beyond Alaska. The subduction zone requires a special evaluation for potential motions.

e. Seismic evidence can complement geological evidence to confirm potentials for earthquakes.

f. Three-dimensional patterns of earthquake hypocenters may help to define the patterns of dominant earthquake fault zones. Such information provides

(1) Depths of movement along a fault.

(2) Details of the dislocation process, notably the separation of rupture segments in space and time.

(3) The presence of active fault segments that have no manifestation at the surface.

g. Focal mechanisms or fault-plane solutions can be derived from seismic records and these can identify the fault movements that generate earthquakes.

h. Small, sometimes infrequent, earthquakes, $M \leq 5.0$, have a widespread distribution that is apparently unrelated to major structural features. They can occur wherever there is some distortion in an otherwise uniform stress field. These occurrences need to be encompassed in broad zones where they can be assigned values for residual, low level seismicity. But, as indicated in Table 2-2, events less than $M = 5.3$ are irrelevant for the safety or operability of water resources structures.

i. Microearthquake networks usually have a system response to peak ground velocities between about 1 Hz and 25 Hz and record earthquakes with magnitudes between 1 and 4.5. Such networks record in a small time frame, days to months, evidences that would be obtained only over many years of observing felt earthquakes. The microearthquakes help to

(1) Define broad areas of seismicity and activity along fault zones.

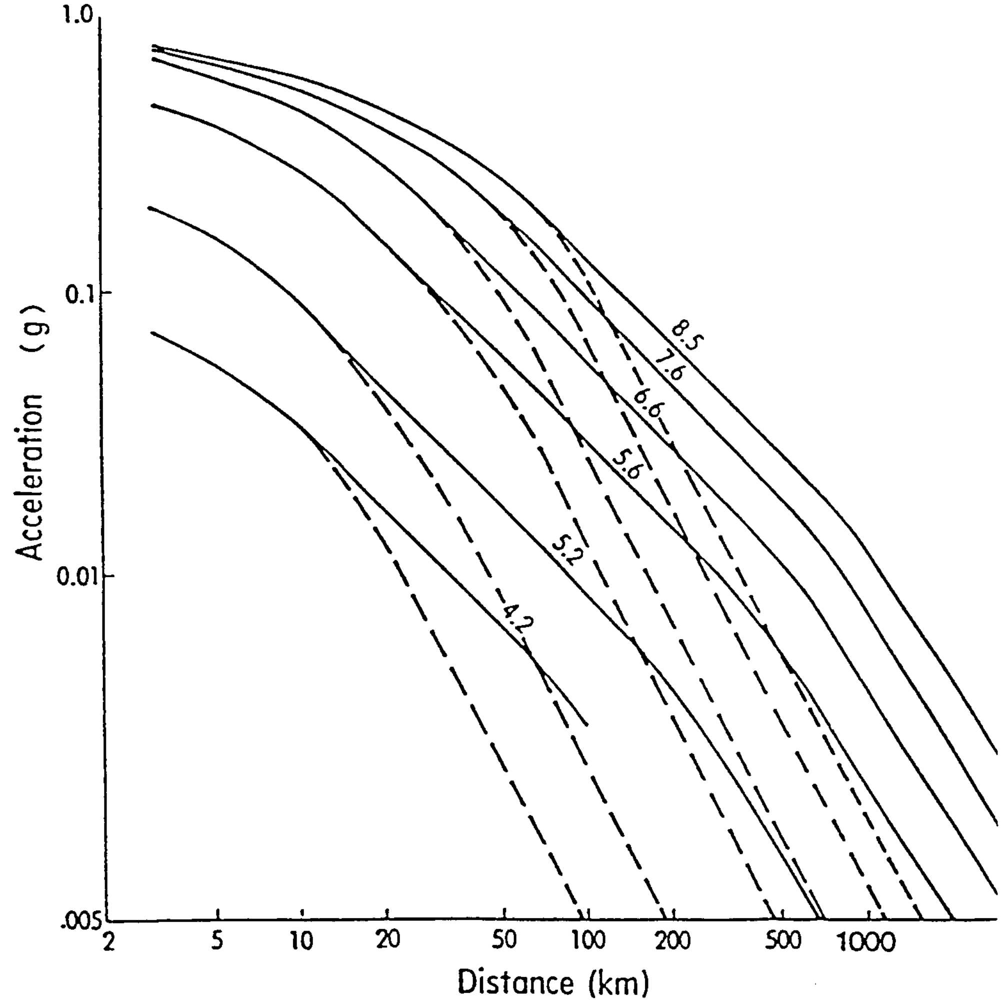


Figure 3-2. Dashed lines with solid lines at distances near the source are attenuations for western United States. Solid lines are modified attenuations for eastern United States interpreted by Algermissen et al. (1982)

(2) Fix the lengths and depths of fault segments, thus assisting in judging the potentials for maximum earthquakes.

(3) Provide focal mechanisms.

(4) Give numerical values on relative rates of recurrence of small earthquakes.

3-4. Recurrence of Earthquakes

a. Recurrence of earthquakes is commonly obtained from seismicity through a b-value which defines the slope of a line in the Gutenberg-Richter magnitude and recurrence relation that indicates both absolute and relative numbers of earthquakes for a given area per unit of time versus either magnitude or intensity. In nature, the smallest earthquakes are the most numerous and earthquakes become progressively fewer as they become larger, thus imparting the slope to this curve. Paleoseismic evidence from geology can be added to the curve. Where large earthquakes have not occurred, or have been statistically too few to be meaningful for recurrence estimation, the b-line is projected to show them. In this way, the b-line is the basis for probabilistic interpretations of seismic hazard.

b. Following are properties of b-lines that pertain to the requirements of engineering:

(1) The expected number of earthquakes of magnitude M or greater occurring within an area can be described by the magnitude-recurrence relation, or b-line, when the area is both large and seismically active: for example, southern California, southwest Japan, the Aleutian arc.

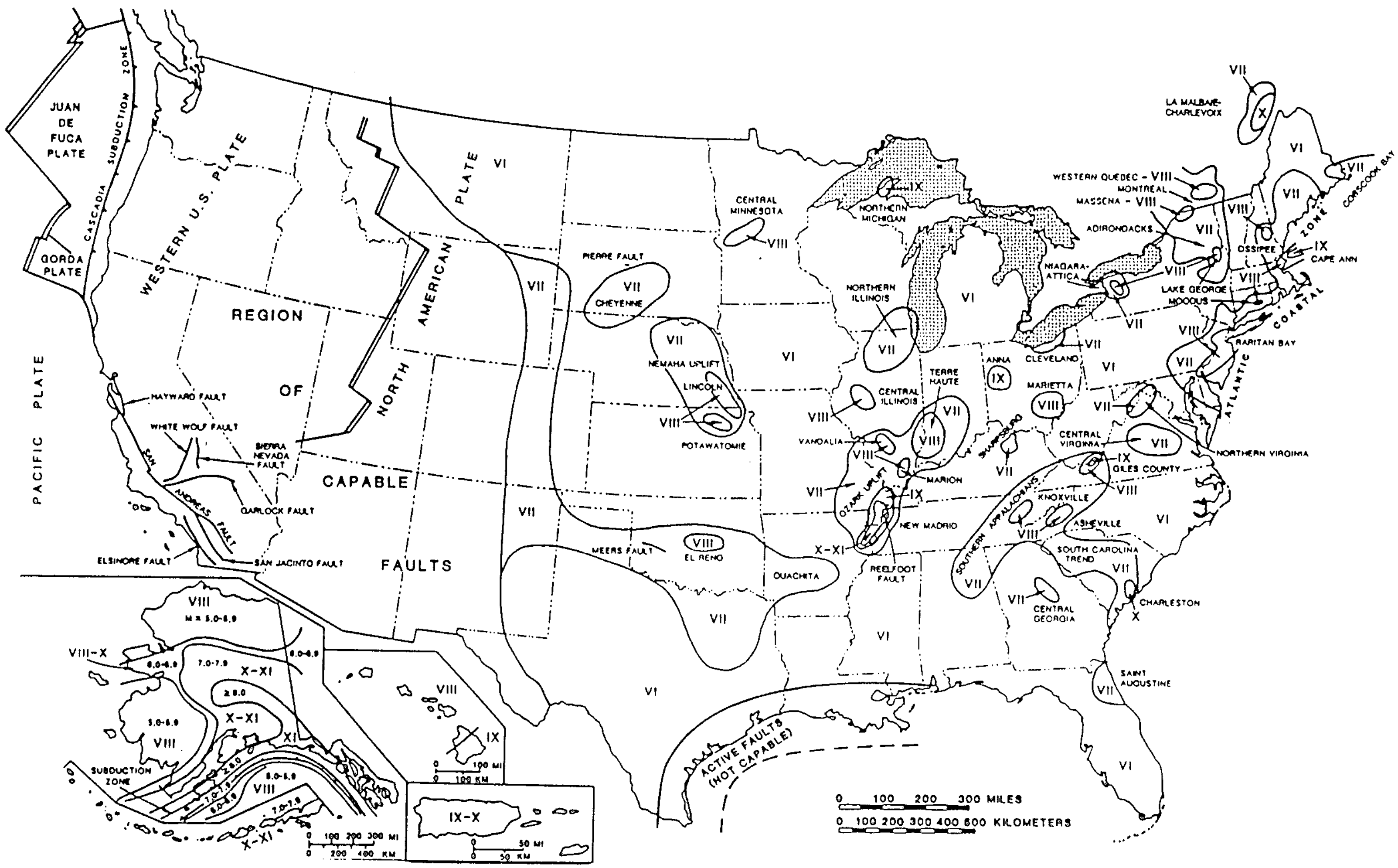


Figure 3-3. Seismic source areas in the United States. From Krinitzsky, Gould, and Edinger (1993)

(2) A b-line valid for a large, seismically active area is not valid for smaller parts of that area.

(3) B-lines do not apply to individual faults.

(4) In seismically inactive areas, central and eastern United States, b-lines are reasonably accurate only for earthquakes of $M \leq 5.0$.

(5) All b-lines are unsatisfactory at $M \geq 5.0$ to 6.0 for use in the engineering of critical structures (see Krinitzsky 1993).

Probabilistic seismic hazard analysis should not be used as the basis for seismic safety designs at Corps of Engineers water resource structures or other critical projects.

3-5. Induced Seismicity

Earthquakes can be induced by quarrying, mining, fluid injection, and the impoundment of reservoirs. With rare exceptions, these earthquakes are shallow, with focal depths to ~3 km, and too small to affect engineered structures. Such earthquakes are unrelated to potentially larger earthquakes that are of tectonic origin. The above-mentioned earthquakes do not provide energy levels that can affect properly engineered structures. Potentially damaging earthquakes must be of tectonic origin, meaning they are rooted in competent rocks at depth where stress drops during rupture can be appreciable. At most, man's activities may trigger such earthquakes, and that can happen only where those earthquakes are on the verge of occurring from natural causes. A geological-seismological evaluation done properly for an engineering site will include those earthquakes. Thus there is no need for special consideration of induced events.

Chapter 4
Geological Evaluation

4-1. Introduction

a. This chapter outlines procedures for the assessment of the regional and local geology at a project. The regional geology is an integral part included in the planning, design, and construction process for Corps Civil Works projects. In project development, knowledge of the geology is essential to the preliminary planning and selection of sites and to interpretation of subsurface exploration data.

b. For new projects, much of the data needed to describe the geology and determine the seismicity are the same. As a consequence, with the exception of detailed fault evaluation studies, the determination of seismicity and the preliminary selection of design earthquakes are done as a routine part of the geologic studies. The engineering seismology requirement for more in-depth studies of tectonic history, historical earthquake activity, and fault evaluation studies is a logical extension of the work.

c. As discussed in Chapter 1, the state of the art in engineering seismology and earthquake engineering evolved rapidly in the early 1970s. Geological studies contained in planning and design documents prepared before the early 1970s are likely to be deficient in information useful for the selection of design earthquakes. As a consequence, new geological studies will be a necessary first step in the procedures leading to the selection of design earthquakes for these older existing projects.

4-2. Objectives

a. The objectives of a geological investigation of earthquake hazards are to

(1) Find those geological features that facilitate the concentration of strain energy and that cause earthquake-producing fault rupture releases.

(2) Estimate the maximum earthquakes that may consequently be generated.

(3) Obtain evidences of occurrences in the recent past.

b. Not always are these matters determinable. Judgment may be needed in order to avoid surprise.

c. These objectives are achieved in combination with the seismological evaluation. Together, they form the basis for selecting the maximum credible and operating basis earthquakes and they facilitate the assignment of defensible earthquake ground motions.

4-3. Criteria

a. Strain energy from tectonism is a regional effect that is concentrated locally. Evidence for concentrations may be found in association with:

(1) Small intrusive heterogeneities in the rocks such as plutons.

(2) Large contrasting features with abrupt lithologic changes such as a boundary between a crystalline massif abutted against a sedimentary basin.

(3) Pronounced flexures in the rocks.

(4) Major rifts, fault zones, and faults.

b. For assessing the above, a combination of geology and geophysics can provide three-dimensional structure and stratigraphy.

c. Geophysical data are obtained generally from

(1) Magnetometer surveys that are best for indicating the deeper structural effects.

(2) Bouguer gravity maps that are more sensitive to shallower effects.

(3) Profiles obtained from seismic surveys.

(4) Boreholes, from which physical properties of the rocks can be determined, including stress levels and directions of stress.

(5) Geodetic surveys.

(6) Surveys of radioactivity.

(7) Anomalies in temperature gradients.

d. Geology-related features that may characterize active tectonism are

(1) Scarps, benches, and shutter ridges.

(2) Offset drainage.

(3) Linear valleys and linear ridges.

(4) Sag ponds.

(5) Truncated spurs of hills.

(6) Displaced shorelines and crustal tilting.

(7) Changed slopes on alluvial fans.

(8) Displaced terraces.

(9) Abrupt changes in stream gradients.

(10) Alignment of landslides.

(11) Abrupt changes in rock types.

(12) Anomalous changes in patterns of joint sets.

(13) Evidences of soil liquefaction.

(14) Springs, hot springs, geysers, and other volcanism.

(15) Vegetation patterns reflecting hydrologic boundaries.

e. The geological information comes from available maps, imagery, overflights, ground examinations, geophysical corroboration, recognition of hydrologic barriers at faults, earthquake history, boreholes, and trenching. Often these are identifiers of faults that are earthquake generating.

f. Imagery is valuable for observing and interpreting surface features. No fault should be accepted as active solely from imagery. It must also be examined on the ground.

g. Another caution is that the collection and analysis of information described above can be almost endless. Judgment must be applied to focus an investigation and to limit its extent so that it furnishes critical information but does not go to unnecessary length. The information should be enough to make the conclusions defensible.

h. Investigation does not end when construction begins. Excavations during construction should be examined by a competent geologist to make sure that no surprises are unearthed and ignored.

4-4. Fault Evaluations

a. Faults are of critical importance in earthquake studies since all earthquakes that are likely to be of interest in engineering are believed to be the result of fault movements.

b. Figure 3-3 shows a broad region covering western United States where earthquake-generating faults can be identified. East of this region, earthquake-generating faults are rarely manifest. Nonetheless, earthquake evaluations in eastern United States should be sufficient to assure that the possibility of existing surface evidence of active faults is not overlooked.

c. Existing faults are sufficient to account for earthquakes so that the possibility of totally new faults can be dismissed. What also must be dismissed in all areas are dead faults as opposed to active ones. Of the active ones it is necessary to distinguish capable faults (capable of generating earthquakes) from those that are active but not capable.

d. A fault can be active, not active, or not determinable. If the fault is active, it is essential to determine if it is capable, or not capable, meaning capable of generating earthquakes.

e. A fault can be active, yet not capable, if it is activated by creep, fluid extraction, salt domes, or gravity slumps. These are moving faults for which there are no maximum credible earthquakes. However, if a fault is not active, or the presence of a fault is not determinable, but there is either historic seismicity or seismicity with paleo-evidence of earthquakes, then a maximum credible earthquake must be assigned on the assumption that earthquake-producing movements have been confined to the subsurface.

f. Comparing capable faults in the plate boundary with those in the intraplate,

(1) Plate boundary faults are relatively greater in length and have a smaller stress drop.

(2) Spreading ridges have tensional faults that are relatively shallow.

(3) Transform faults are strike-slip and relatively shallow.

(4) Subduction zone faults are compressional and relatively deep.

g. In the intraplate, judging from microseismicity patterns in the New Madrid area, the faults are

(1) Relatively shorter and have greater stress drops.

(2) The faults can be either compressional or tensional.

(3) They can be shallow or deep.

4-5. Ground Surface Displacements

a. Dating of paleoseismic events sometimes can extend the knowledge of historic earthquakes and of historic fault movements, though for the latter it must be kept in mind that earthquakes do not occur uniformly through time. Examples of possible datable paleoseismicity are

(1) Displacements on faults where ages or number of events can be identified.

(2) Sudden burials of marsh soils.

(3) Trees killed by a rise in water level.

(4) Disruption of archaeological sites.

(5) Liquefaction intrusions cutting older liquefaction.

b. Age dates taken for isolated points along a fault scarp can be extended appreciably by tracing analogous morphological features along the fault scarp.

c. A long fault, like the San Andreas or the Wasatch, does not move along its entire length during an earthquake. A segment moves. Another earthquake moves a different segment. Then, when most segments have moved, the process repeats, but it may not produce the same segment lengths nor follow the same time pattern. The lengths of these segments can be found in the historic evidence and, if that is missing, they can be interpreted from the geomorphology. The maximum throw or displacement of the fault during an earthquake can be obtained similarly. These dimensions are then entered into charts, based on earthquakes from around the world, that relate measured fault dimensions to earthquake magnitude.

4-6. Relation of Fault Size to Earthquakes

a. Bonilla, Mark, and Lienkaemper (1984) developed several valuable statistical comparisons for dimensions of fault movement and earthquake magnitude. Their work is based on 58 moderate to large earthquakes with shallow focal depths and with surface expression. Another notable compilation was made by Wells and Coppersmith (In press) based on 361 historical earthquakes. Such work is useful but must be used with caution because earthquakes of large size can occur without fault rupture at the surface. Also, the data do not apply at all to subduction zone earthquakes. Figure 4-1 shows length of surface rupture versus earthquake magnitude and Figure 4-2 shows surface displacement versus magnitude. The lines in both diagrams represent means. To encompass the dispersion in the data, one would need to move the lines appropriately to bracket this spread.

b. Another aspect of the length-to-magnitude relationship is presented by Kanamori and Allen (1986) in Figure 4-3. This figure introduces recurrence intervals in years for a selection of individual earthquakes. Earthquakes that reoccur frequently are seen to move along greater fault lengths than those that occur infrequently. The logic is that with an increase in time a fault has a greater chance to heal, allowing a greater stress accumulation and a greater stress drop per unit area of fault rupture, thus resulting in a greater earthquake when it occurs.

c. Scholz, Aviles, and Wesnousky (1986) expanded this concept of healing to distinguish plate boundary from intraplate earthquakes, comparing length to moment magnitude as shown in Figure 4-4. They also made a further comparison of slip rate on the causative faults with recurrence times for earthquakes. They note a slip rate on plate boundaries that is 100 times greater than that of the intraplate. They indicate that a knowledge of the slip rate, combined with other information on tectonism, can aid in designating earthquake potentials.

d. Yet another approach is that which involves the fault area, meaning the areal extent of the fault plane that ruptures. The fault area, which sometimes can be judged from microearthquake data, is no doubt more directly related to energy release than is fault length. Comparisons then are based on seismic moment as was done in Figure 4-4.

e. Finally there is the very common situation, previously mentioned, where fault movement is not to be found at all on the ground surface. These are source areas that must be treated both in the manner of seismic zones and of capable faults. Also, great refinements in statistical sums of the measurements of faults at the ground surface do not necessarily bring the answers that are needed. Be prepared to examine all modes of possible interpretation and to rely in the end on professional judgment.

4-7. Relation of Fault Type to Earthquake Ground Displacements

a. Structures may have been or may have to be built across faults. For all such structures, it is needful to assess how fault movements may break the ground surface.

b. Cluff, Slemmons, and Waggoner (1970) have illustrated the character of typical surface effects that

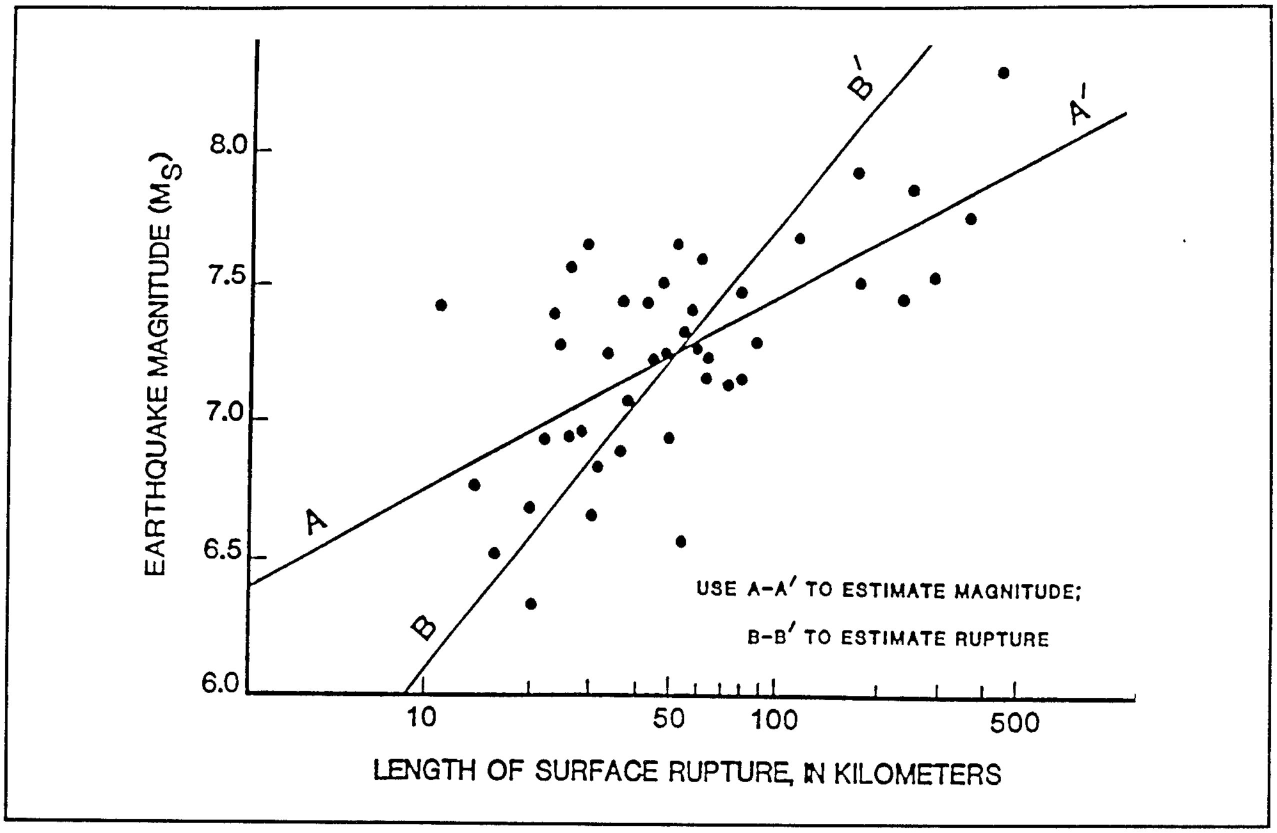


Figure 4-1. Relation of length of surface rupture to earthquake magnitude (Bonilla, Mark, and Lienkaemper 1984)

result from fault movement. They point out that there are distinct differences in ground breakage that are dependent on the types of faults that are involved.

(1) Strike-slip fault. Movement on a strike-slip fault is shown in Figure 4-5. A strike-slip fault is usually steep, nearly vertical. It is apt to produce a very narrow band of displacement effects. Movement occurs along a pre-existing plane. Vertical components are small.

(2) Normal fault. A normal fault, Figure 4-6, has more pronounced topographic effects. The downdropped block breaks along the dragged lip and forms secondary displacements. Damage by displacements is concentrated in the downdropped block while the upthrown block may remain relatively intact. Normal faulting is also susceptible to movement along multiplane, steplike fault blocks.

(3) Thrust fault. A thrust fault, Figure 4-7, tends to break up in the upthrown block and the downthrown block remains intact. Landslides may extend onto the downdropped block. Field measurement of the amount of thrusting in the past may be difficult because of this obliteration of the fault plane. The breakage in the upthrown block tends to be arcuate and irregular. Thrust faulting also can occur along multiple planes of movement.

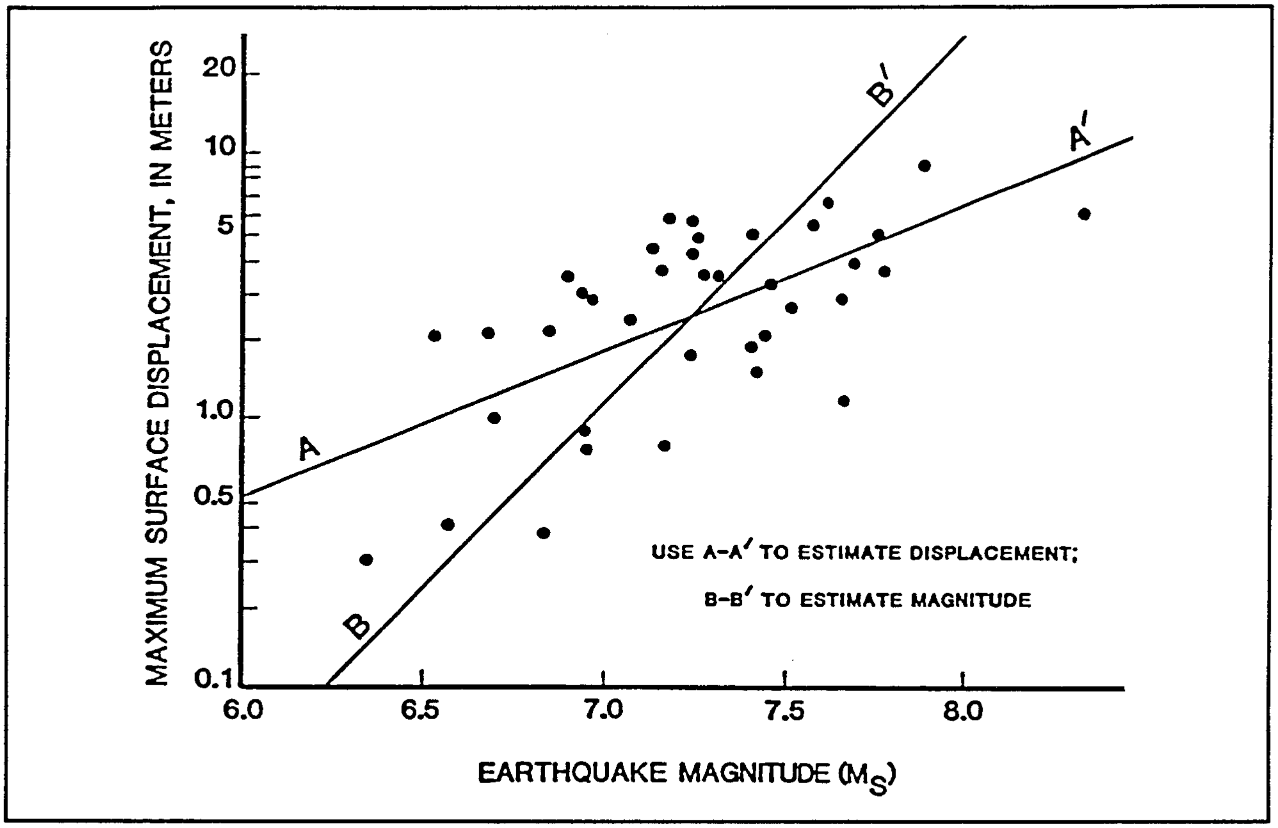


Figure 4-2. Relation of maximum surface displacement to earthquake magnitude (Bonilla, Mark, and Lienkaemper 1984)

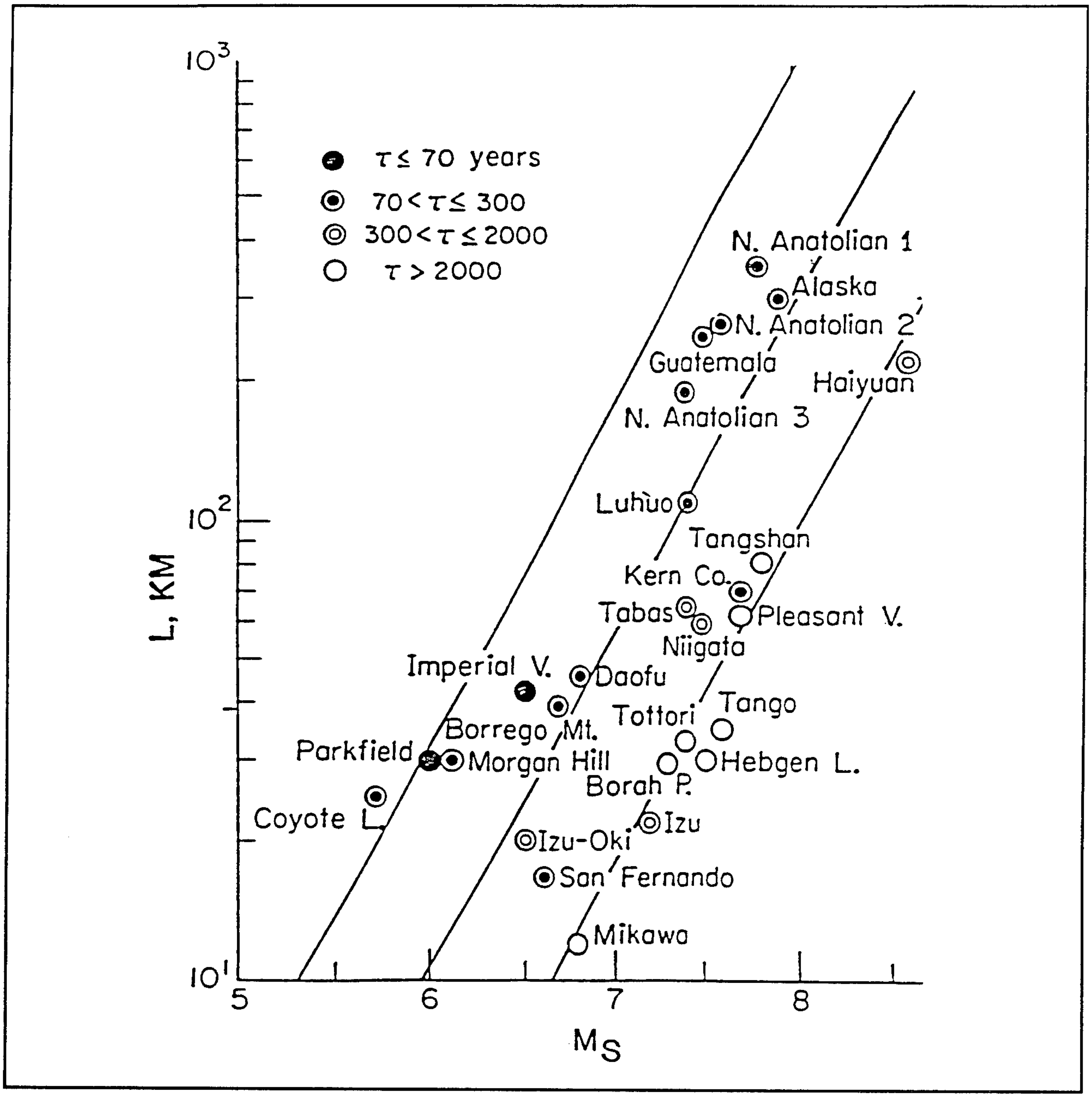


Figure 4-3. Relation of length of fault rupture at the surface to earthquake magnitude and recurrence time in years. The lines show a general trend whereby earthquakes of comparable magnitude that occur less frequently occur on shorter fault lengths (Kanamori and Allen 1986)

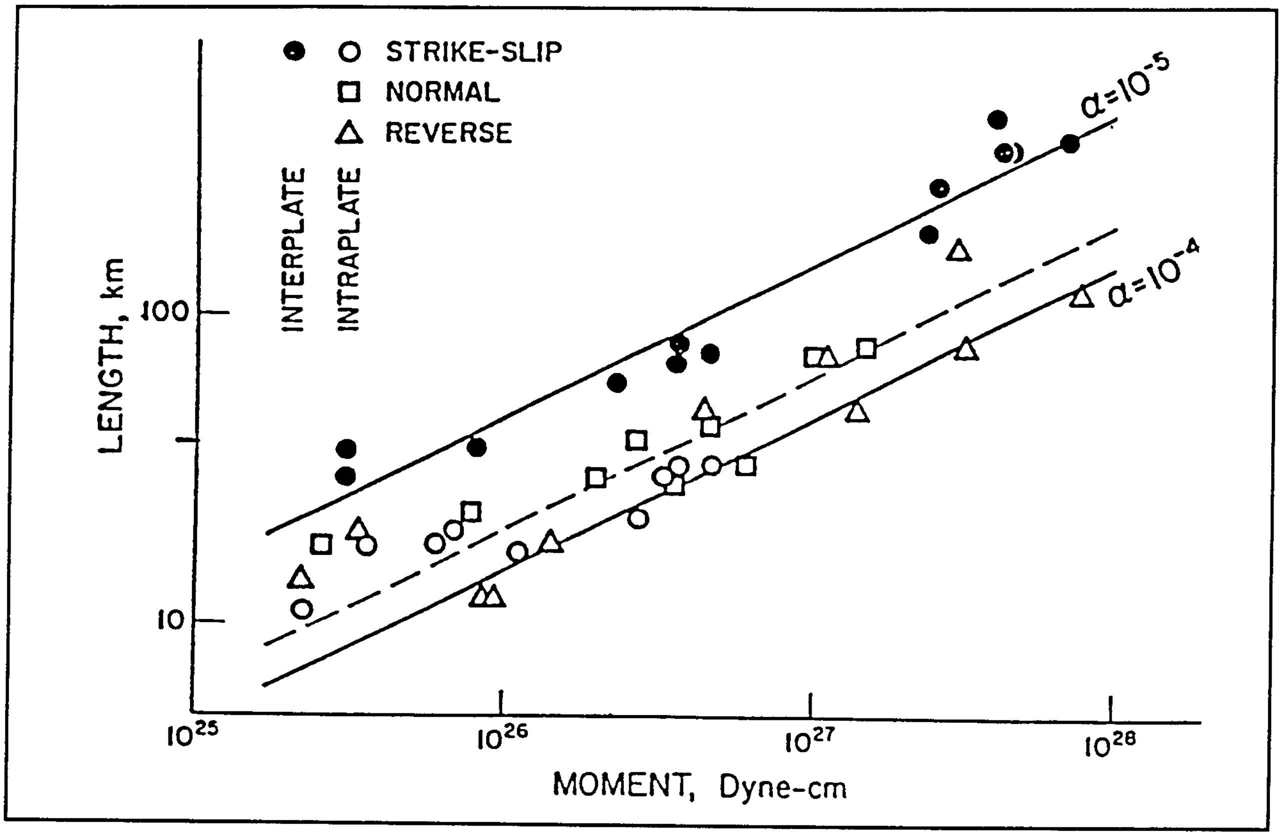


Figure 4-4. Scaling differences between length of fault rupture and seismic moment for plate boundary and intraplate areas (Scholz, Aviles, and Wesnousky 1986)

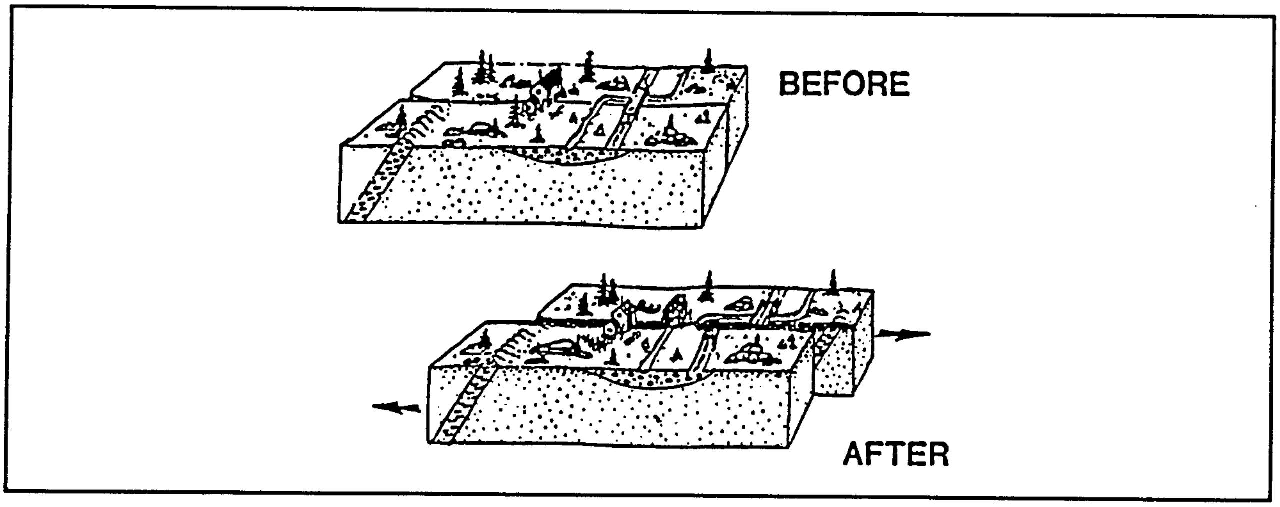


Figure 4-5. Damage associated with movement along a strike-slip fault (Cluff, Slemmons, and Waggoner 1970)

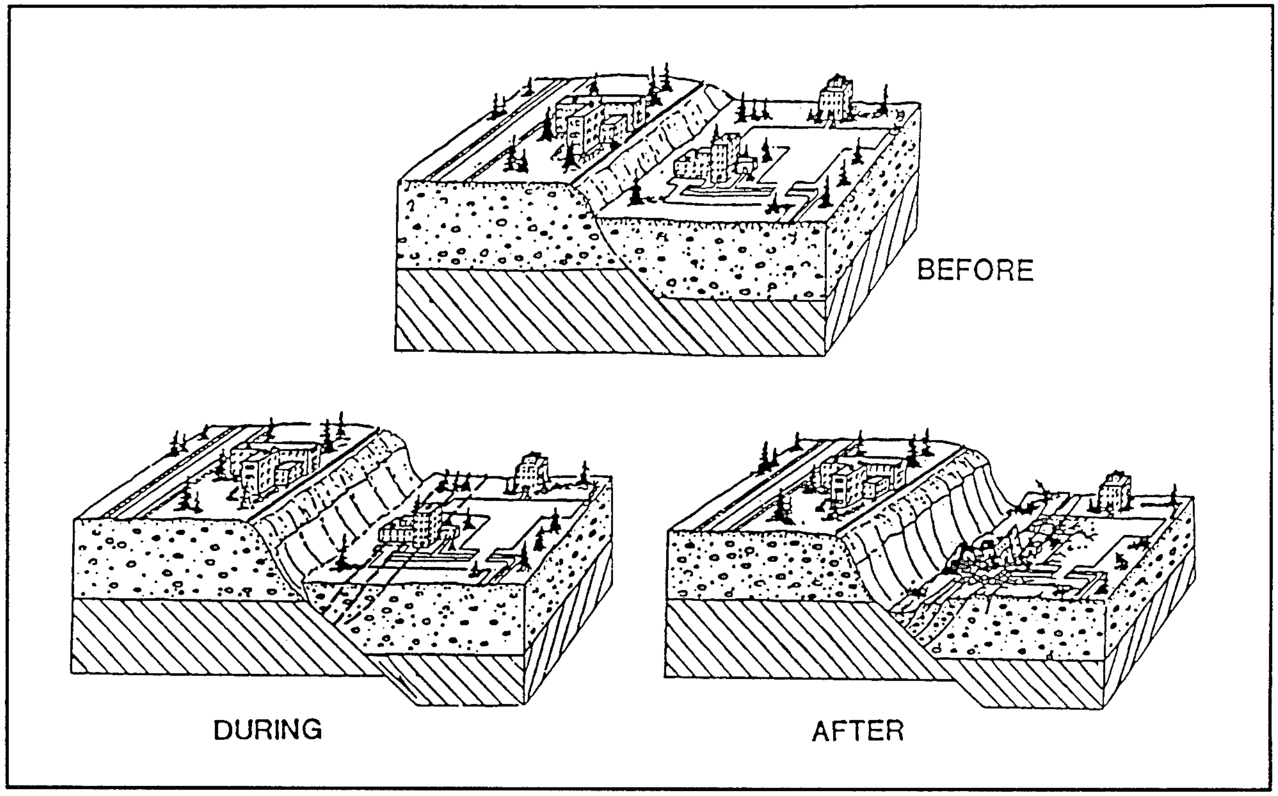


Figure 4-6. Damage from a normal fault. Displacements are induced in the downthrown block at a distance from the fault trace (Cluff, Slemmons, and Waggoner 1970)

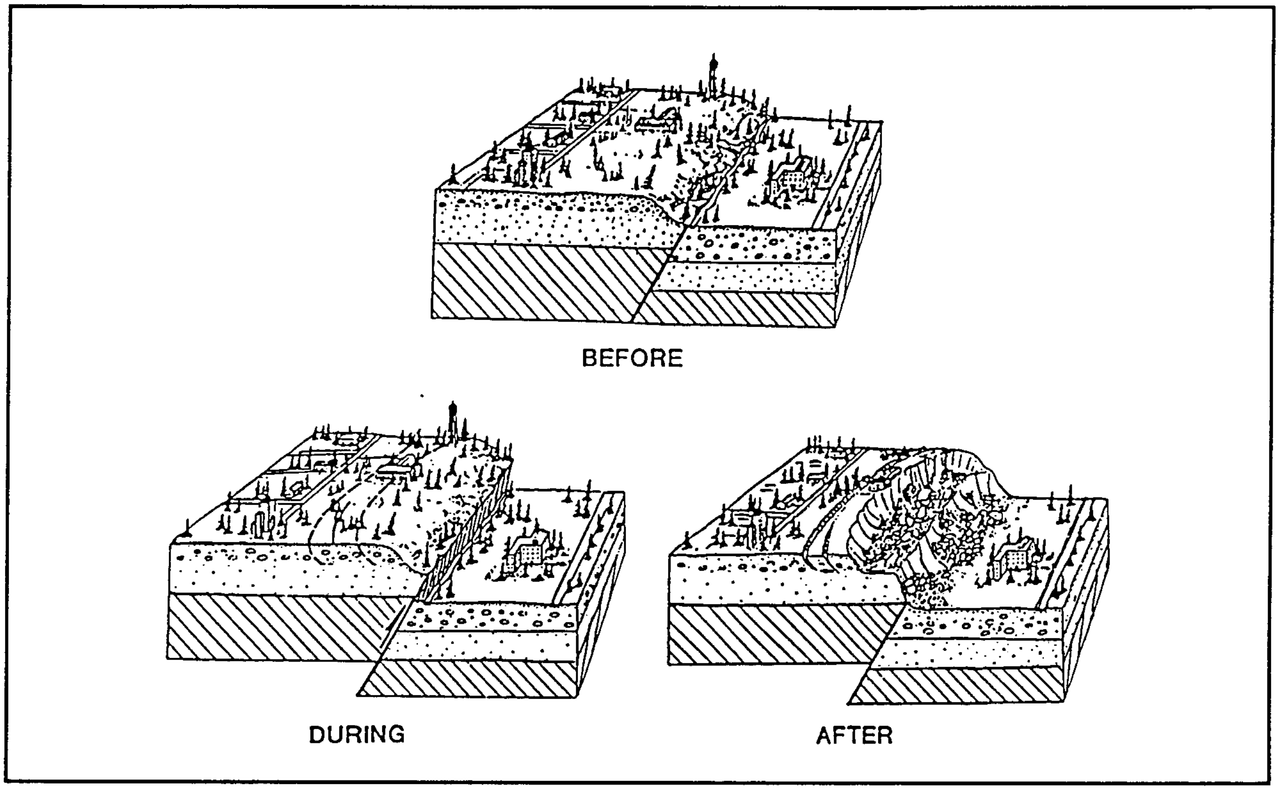


Figure 4-7. Damage from a thrust or reverse fault. Displacements are induced in the upthrown block (Cluff, Slemmons, and Waggoner 1970)

Chapter 5
Map Sources for Earthquake Ground Motions

5-1. Introduction

Numerous maps are available that provide generalized seismic values in an easily accessible manner. Only a few that are representative will be mentioned in the following sections. The data available in these maps usually are unsuitable for the requirements of critical projects and their use for design should be restricted to either areas of low seismicity or for structures of low criticality. However, these maps have a special use as a first step in evaluating whether or not to undertake site-specific geological-seismological investigations.

5-2. Characteristics of Maps

Most published maps can be characterized as follows:

a. The maps generalize information that is unevenly distributed and of uneven quality.

b. Microzoning for locally varying foundation conditions or for local effects of faults are not accommodated.

c. Maps that specify categoric ground motions or give coefficients for motions commonly do so for *effective* motions, eliminating peak values that are judged to have little likelihood of being experienced. Effective motions are an entrance into the maps of attempts to consider costs in designing for earthquakes whose sources and sizes are uncertain.

d. The above considerations are generalized in the maps, sometimes crudely, seldom with any explanation of what was done.

5-3. Seismic Coefficient Maps

a. The seismic coefficient is a dimensionless unit obtained as the ratio between the acceleration for an appropriate spectral content and response in a structure with the acceleration of the ground. Thus, each seismic coefficient map is constructed for a specific type of structure. An example is Figure 5-1 which shows coefficients mandated by ER 1110-2-1806 for analyzing concrete dams. Structures in Zones 0 to 2 may be tested by pseudostatic analyses using the coefficient given on the map. Structures in seismic zones 3 and 4 may be analyzed by the pseudostatic method or they may require dynamic analyses if they are large enough to pose potential hazards to life or property. The map designates the areas in which structures require specified analyses. Structures in Zones 3 and 4 may be required to have geological-seismological studies to provide site-specific ground motions.

b. Seismic coefficient maps sometimes contain factors that modify the coefficients for different grades of construction and for differences in foundation conditions.

c. An important coefficient map for seismic evaluation of buildings is that of the Applied Technology Council shown in Figure 5-2. The map is for acceleration-based coefficients, shown as A_a. There are also Applied Technology Council velocity-based coefficients, A_v. Included in these coefficients is a judgmental factor, representing experience on the part of structural engineers. There is no direct way to relate the coefficients on this map or on any other map of this sort to motions recorded by strong motion accelerograph instruments.

5-4. Seismic Intensity Maps

A variety of seismic intensity maps are available that combine attenuated effects from multiple sources. Figure 3-3 shows interpretations for maximum intensities in seismic source zones in eastern United States and Alaska, Hawaii, and Puerto Rico. The source intensities must be attenuated from source areas to a site. Such maps can be made for fault sources in western United States but they need to be on a scale that allows more detailed treatment.

5-5. Maps of Earthquake Ground Motions

a. Algermissen et al. (1990) developed maps that show peak horizontal ground motions as acceleration and velocity for 90 percent probability of nonexceedance in 50 years, and acceleration and velocity for 90 percent probability of nonexceedance in 250 years. The motions are mean values on rock.

b. Where noncritical structures are concerned, the use of seismic parameter maps has been incorporated into building codes and other established procedures.

c. For noncritical structures and for operating basis earthquakes for critical structures, where motions impact purely economic decisions, probabilistic seismic motions from maps can be used.

d. An important acceleration map for California was prepared by Mualchin and Jones (1992) for use by the California Department of Transportation (Caltrans). A portion of the map is shown in Figure 5-3. The map is

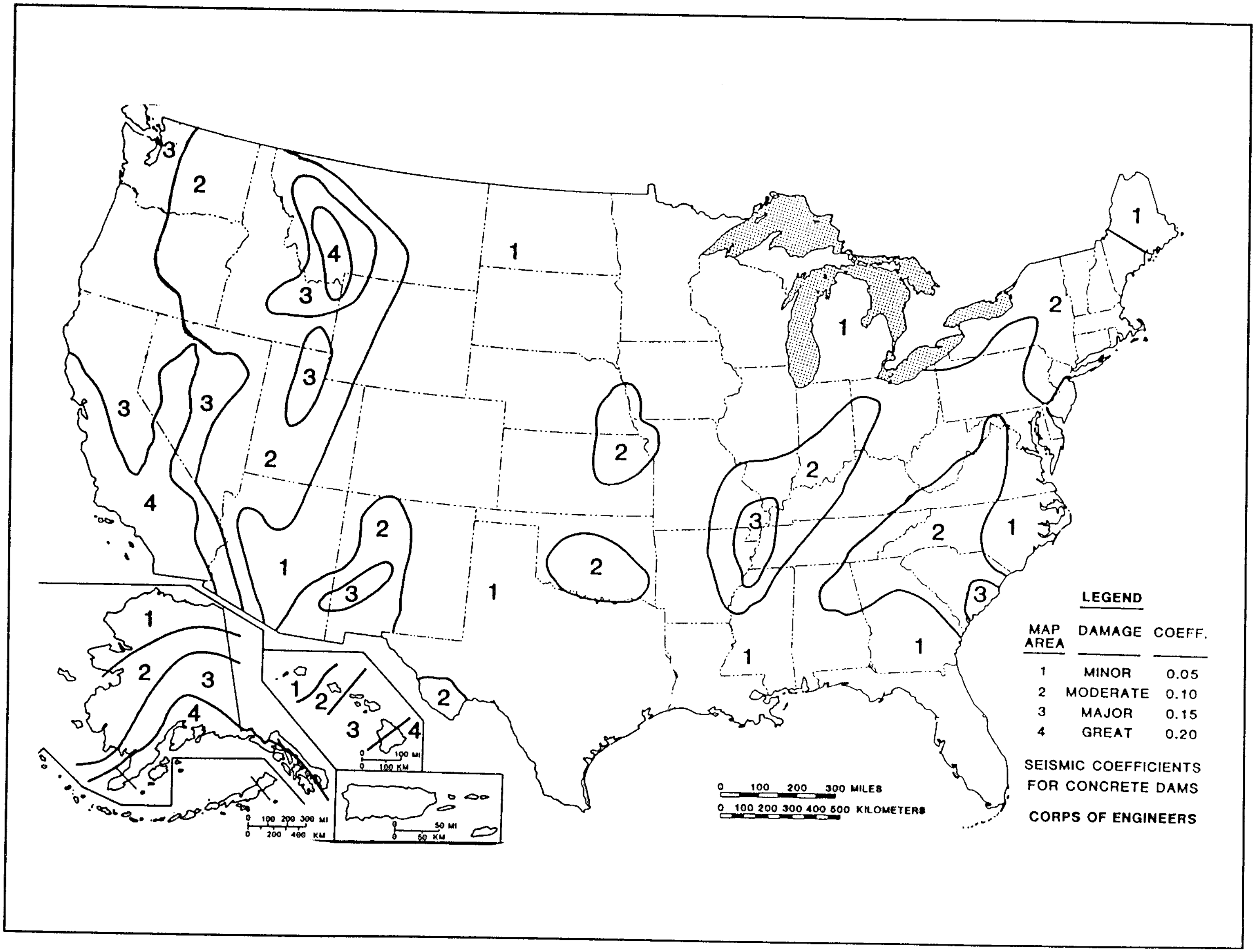


Figure 5-1. Coefficients for evaluating noncritical concrete dams. Modified from ER 1110-2-1806

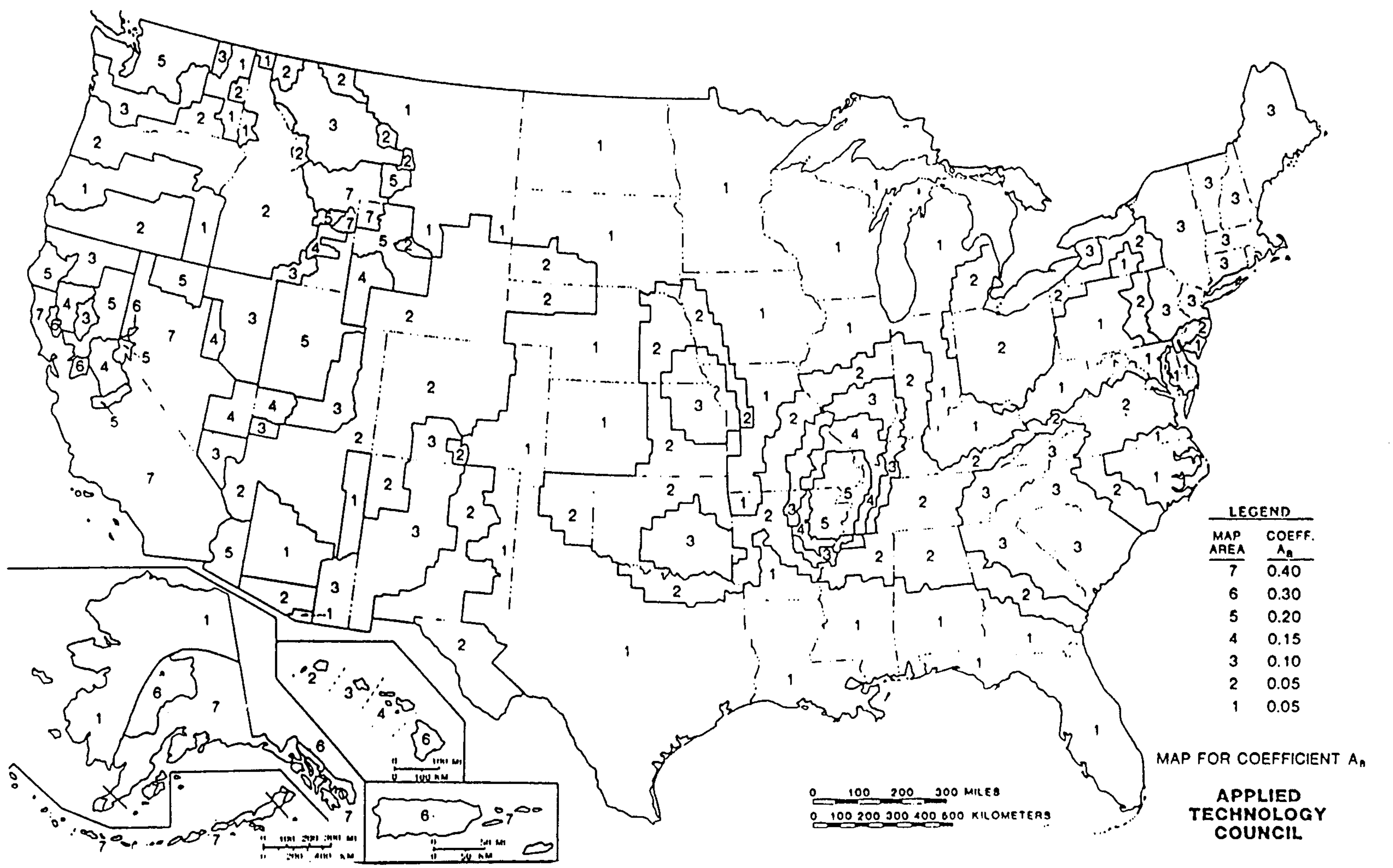


Figure 5-2. Acceleration based coefficients for evaluating buildings. Applied Technology Council (1978)

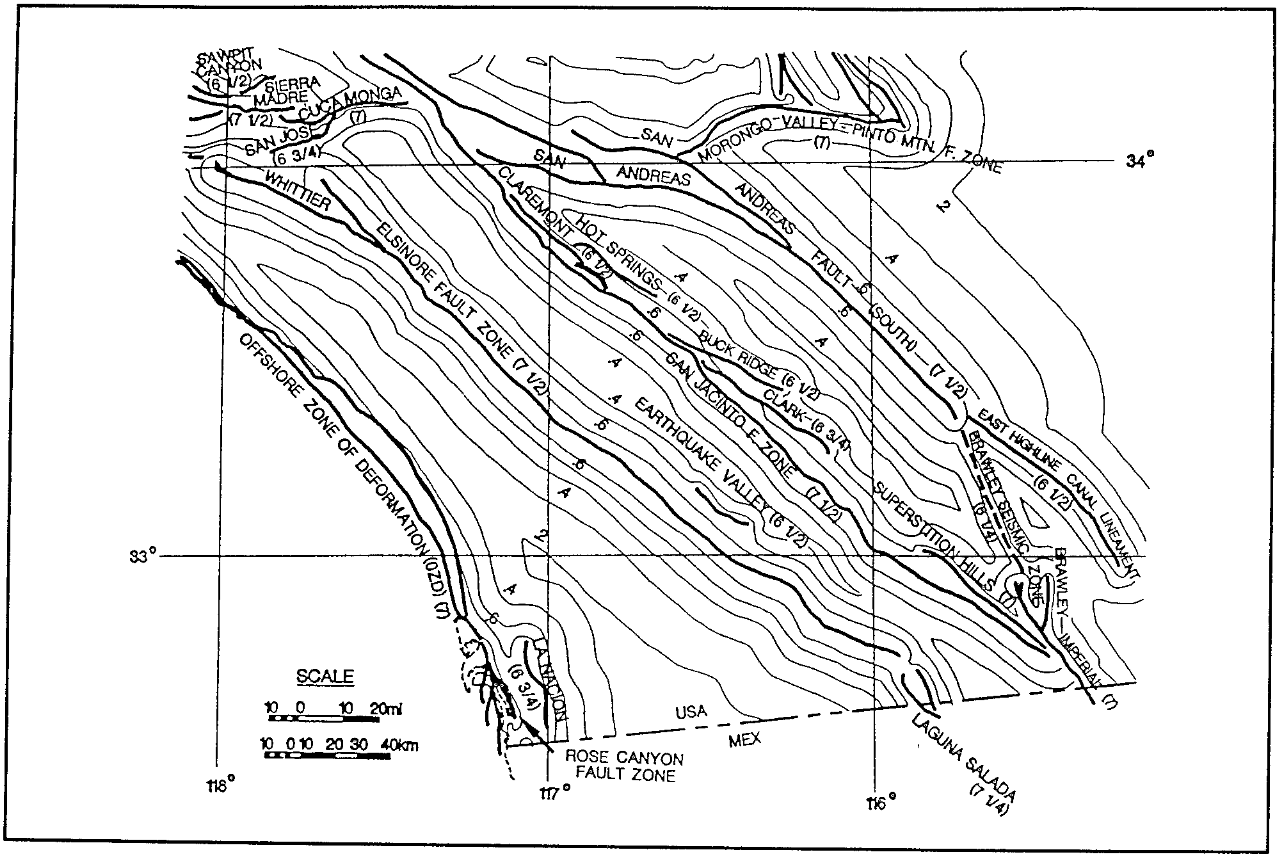


Figure 5-3. Detail from map of peak acceleration (g) for maximum credible earthquakes in California on rock and stiff soil sites. From Mualchin and Jones (1992)

non-probabilistic. It shows geographically the spread of motions at rock and stiff-soil sites for maximum credible earthquakes on important faults. The principle involved is that a critical structure must be prepared to resist the worst that can happen tomorrow regardless of its probability. For a critical engineering site, a further examination is needed to check these evaluations locally, but the map can be extremely useful in planning.

5-6. Applicability of Maps

Nuclear power plants, facilities for liquid petroleum gas, major dams that can cause severe losses upon failure, hospitals, schools, and other installations that are either sensitive or potentially dangerous are critical structures that require individual, site-specific investigations on which to base the specification of earthquake ground motions. Published maps will not be sufficiently dependable for these specifications. However, such maps can be sufficient for some critical structures if a structure is located in an area of very low seismicity. This manual provides guidance for determining such situations in Chapter 7. Maps have an additional use as a first step to decide whether or not to undertake site-specific geological-seismological investigations.

Chapter 6
Considerations in Assigning Earthquake Ground Motions

6-1. General Considerations for Assigning Earthquake Ground Motions

a. Assignment of earthquake ground motions for design can be either of two types: site specific or non-site specific.

b. The motions preferably should be deterministic, but under some circumstances may be probabilistic.

c. Motions can be generated that are either calculated (theoretical) or derived empirically.

d. Motions may be based on either earthquake intensity or earthquake magnitude.

e. And motions are selected that reflect the regional setting, whether it is a shallow plate boundary, a subduction zone, or an intraplate area; the site condition, whether some form of rock or soil; the specific earthquake source or sources; and the attenuations for motions from the sources to the site.

6-2. Plate Boundary Versus Intraplate Areas

a. Plate boundary and intraplate areas have markedly different attenuations in the far field. Figure 6-1, modified from Nuttli, compares the areas of MM intensity for approximately equivalent earthquakes in these regions. The San Francisco and New Madrid earthquakes are compared for approximate magnitudes in the range of M = 8, also San Fernando and Charleston for approximately M = 6.5 to 7.0. In terms of areas affected, the comparative factor is about ten.

b. Charts for attenuations of MM intensities over the United States provided by Chandra (1979) are shown in Figure 3-1. Each regional curve shows the reduction in MM intensity from the source area over the distance to a site.

c. There is a total absence of strong motion records for large earthquakes in the intraplate area. To a limited extent, interpretations can be scaled upward from the strong motion records of small and moderate earthquakes, but a factor of 2X is the limit (see Vanmarcke 1979). However, plate boundary earthquakes can be changed to the intraplate by adjusting their attenuation rates and their spectral compositions to accord with what is known or inferred for the intraplate. A simple method for adapting western United States motions (peak horizontal

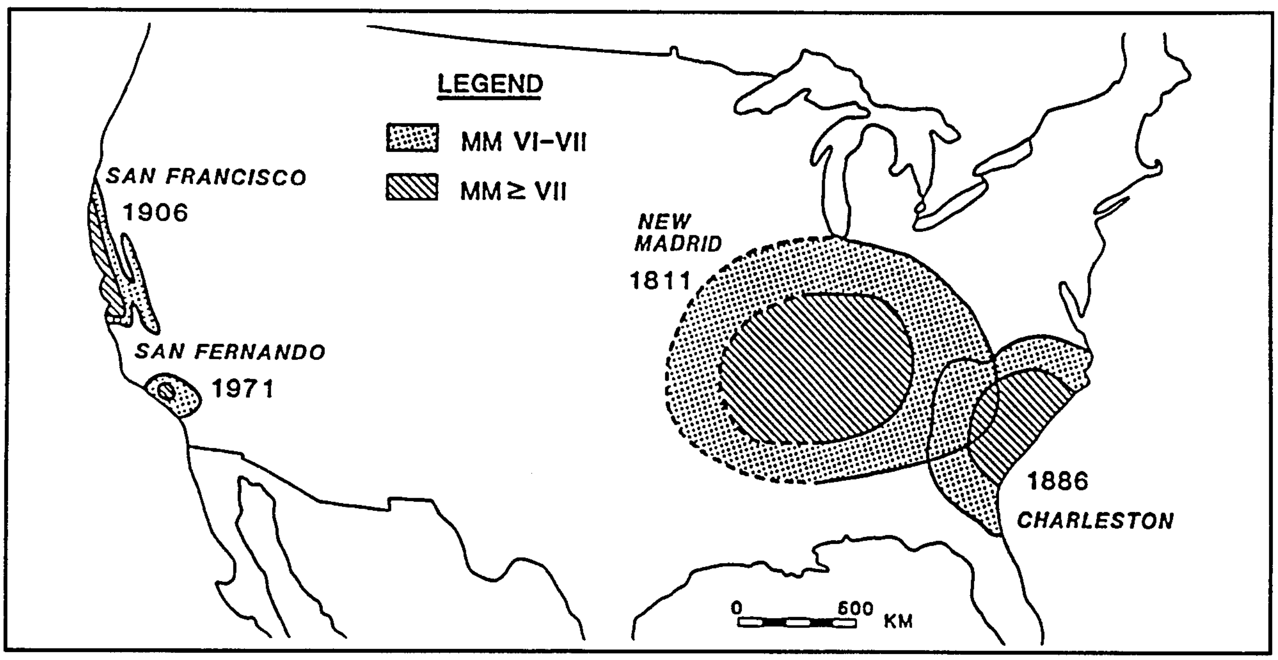


Figure 6-1. Felt areas of equivalent earthquake in the plate boundary of western United States and the intraplate of eastern United States (Nuttli 1974)

acceleration on rock for magnitude and distance from source) to eastern United States is illustrated in Figure 3-2. The figure is from the procedure used by Algermissen et al. (1982) for the preparation of maps showing peak motions on a probabilistic basis for the contiguous United States. A similar construction was used by those authors for peak horizontal velocity on rock. There also are curves that were devised specifically for the intraplate (see Nuttli 1974).

6-3. Site-Specific and Non-Site-Specific Motions

a. The site-specific procedure is required for maximum credible earthquakes developed for critical structures in seismically active areas. A non-site-specific procedure may be used for operating basis earthquakes, non-critical structures, or all structures, whether critical or non-critical, when in an area of low seismic threat. Criteria for these categories are provided in Chapter 7.

b. For non-site-specific evaluations one may use the appropriate seismic zone maps. These are sufficient to provide general design values and to offer very general approximations in terms of probability of recurrence of peak motions. Site examinations may be needed to examine foundation soils, the possible presence of an active fault beneath a structure, and the potentialities for landslides or other hazards.

c. Site-specific evaluations require a full range of studies that identify earthquake sources, the maximum earthquakes to be expected, and time histories of earthquake ground shaking appropriate for the construction site. A caution is that geological and seismological studies to obtain this information can be limitless. One should do only that which is enough to provide a dependable and fully defensible set of decisions regarding ground motions.

6-4. Strong Motion Accelerograms

a. Earthquake ground motions for applications in engineering are recorded by strong motion accelerograph instruments. They differ from observatory seismographs. The latter magnify motions enormously, causing distortions in the spectral composition and records go off scale when the instruments are located near an earthquake source. The strong motion instrument is much less sensitive. It begins to record when triggered, usually by a horizontal acceleration of 0.01 g. Three components of motion are recorded, two for horizontal motions at right angles and one for the vertical. The instrument will record strong peak motions successfully for accelerations up to about 2 g.

b. Records from strong motion instruments throughout the world are generally comparable to each other for spectral compositions of waves up to about 10 Hz. For greater than 10 Hz, the SMAC instruments used in Japan show markedly reduced sensitivity.

c. Figure 2-2 shows a typical processed record for strong motion in one horizontal direction. The recording was processed to present acceleration, velocity, and displacement. The velocity and displacement were produced by integrating the acceleration. Similar presentations are produced for the other horizontal component and for the vertical. Normally, response spectra are generated concurrently and this is shown in Figure 6-2.

d. To obtain duration of strong shaking, there are essentially two procedures, a summation method by Trifunac and Brady (1975) and a bracketing method by Bolt (1973). The Trifunac and Brady method integrates the square of the acceleration until the growth of the curve levels off, then 5 percent is removed from each end of the curve to disallow noise. The time span that remains is the duration. Bolt takes a threshold acceleration and measures the time between first and last intercepts of this level by the acceleration. While the threshold can be taken at other levels, in this manual bracketed duration is based on 0.05 g.

6-5. Response Spectra

a. Response spectra show the vibration of an earthquake in a form that can be used to relate to vibration effects within a structure. An accelerogram and its equivalent tripartite response spectra can be seen in Figure 6-2. To model the energy dissipation effects inherent in a structure, a damping of the response of a single degree of freedom system to earthquake motions was introduced. The ratio of the damping to critical damping is expressed in percent. Thus, the response spectra produced for the strong motion record in Figure 6-2 contain maximum pseudo-acceleration, relative pseudo-velocity, and relative pseudo-displacement. These are expressed for damping at 0, 2, 5, 10, and 20 percent.

b. Note in Figure 6-2 that the response spectra have numerous sharp peaks and valleys. The valleys might not be present at the same periods had another equally appropriate accelerogram been examined. Therefore, it is common practice to select a group of records scaled to the same peak acceleration or velocity and test the structure using them individually. Another common approach is to smooth the peaks and valleys. This can be done with the single record and it can be done as well with the averaged records.

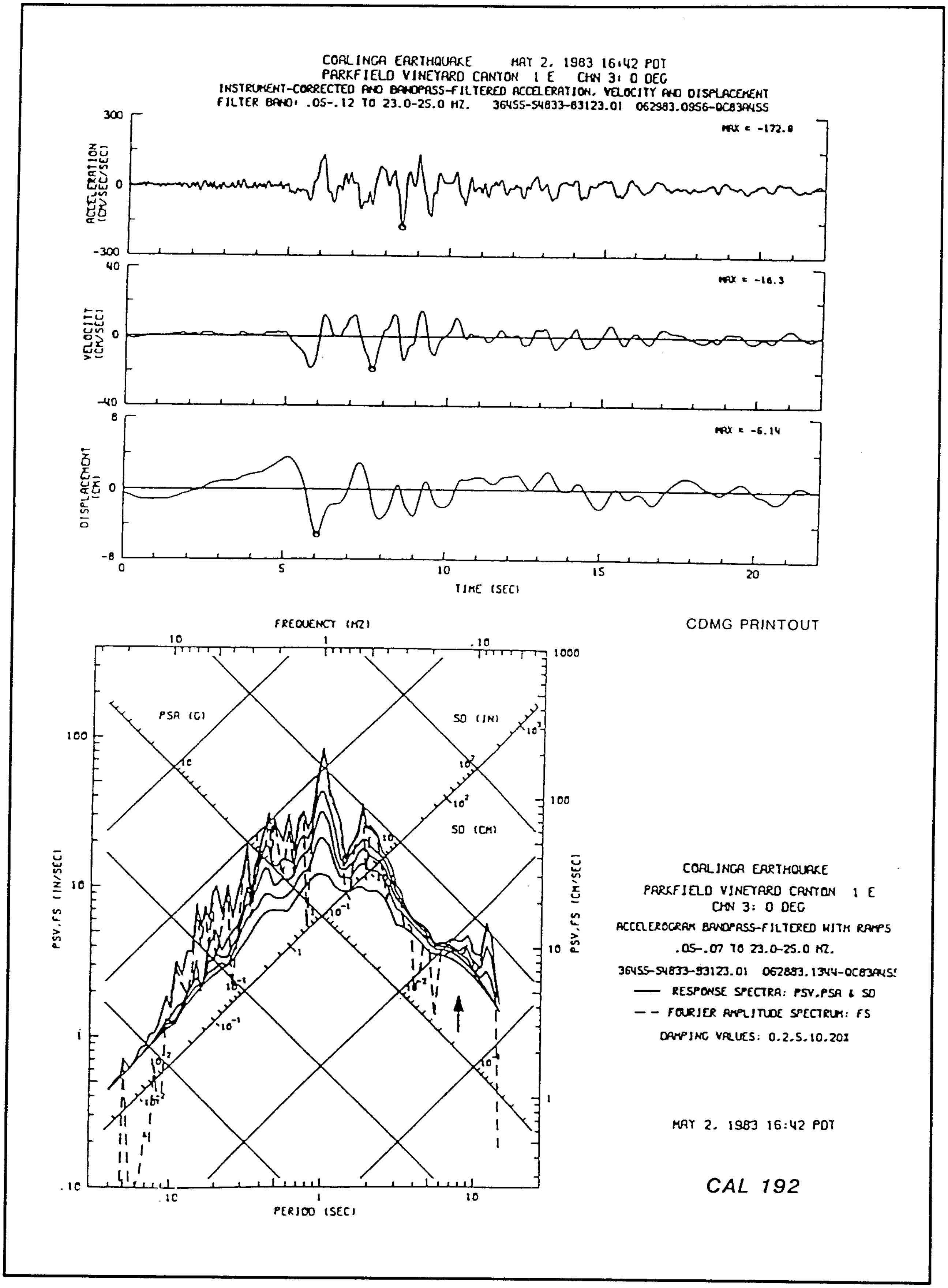


Figure 6-2. An accelerogram with its tripartite response spectra. From Leeds (1992)

c. Where multiple records are combined in the form of response spectra, whether they are smoothed or not, they can be given a range of values such as the mean and mean plus one standard deviation.

d. Preparation of the diagrams for response spectra is done routinely during the processing of strong motion records. The diagrams should be available from the same sources that provide the records. Spectra are strongly influenced by the data processing techniques used, and the effects of these techniques on individual records of interest should be examined.

6-6. Theoretical Versus Empirical Procedures

a. The WES RASCAL computer code for synthesizing earthquake ground motions developed by Silva and Lee (1987) is representative of computerized techniques for specifying earthquake ground motions. Following are essential elements in the procedure:

(1) Uses random vibration theory. Adjusts spectra of actual strong motion records through a theoretical Brune modulus.

(2) Input requirements.

(a) Source depth.

(b) Stress drop.

(c) Density.

(d) Epicentral distance.

(e) Shear wave velocity.

(f) Attenuation.

(g) Moment magnitude.

(h) Frequency range.

(i) Site amplification (soil or rock).

(j) Spectral damping.

(3) Levels for printouts.

M	R (km)
<4.5	<30
<4.5	>30
4.5-5.5	<30
4.5-5.5	>30
etc.	

(4) Accelerogram range. The WES RASCAL program accepts one to seven accelerograms from selected earthquakes. Adjustments applied by the program to these accelerograms serve to form the accelerograms that are produced.

(5) Products.

(a) Synthetic accelerogram (acceleration; velocity, displacement).

(b) Peak values (acceleration, velocity, displacement).

(c) Root mean squares (acceleration, velocity).

(d) Frequency composition.

(e) Response spectra (1 to 10 percent damping, also for target frequencies).

(f) Fourier acceleration spectra.

(g) Spectral ratio (synthetic with actual).

b. The results are dependent on two things: the accelerograms that are fed into the system, and the physical constraints (input parameters) that mostly have to be estimated.

c. The program has the problems that are inherent in all current theory-based synthetic motions. It is weak on reflecting the enormous ranges that exist in the observed strong motion data for any given set of field conditions and is greatly dependent on assumptions for the physical constraints. Those are enormously important but have to be assigned arbitrarily for lack of tangible values.

d. Empirical procedures go through the same general steps to identify the sources of earthquakes, their maximum potentials for magnitude or epicentral intensity, attenuations to the site, and selection of peak values for earthquake excitations at the site. Instead of developing synthetic seismograms for the site the empirical approach would select one or several analogous accelerograms from the catalogue of strong motion records. They would be analogous for the approximate size of earthquake, distance from source, type of faulting, site condition, and whatever other factors that might be relevant. These earthquake records would then be scaled, or adjusted, to fit the maximum acceleration or velocity estimated for the site, and the adjusted records would be used directly in dynamic analyses.

e. Currently the empirical methods are as accurate or better as any that are based on theory and they are also the quickest, the easiest, and the least expensive procedures to use. For these reasons empirical procedures for assigning site-specific motions are preferred. These will be described in Chapter 7.

6-7. Effects of Site Conditions

a. The effects of local or site conditions on earthquake ground motions are complex and important. The motions can be affected by dynamic soil and rock properties, topography, layering characteristics, discontinuities and inhomogeneities, linear versus nonlinear strain dependent effects, and material damping. These material properties may cause reflection and refraction of seismic waves, impedance mismatches, scattering, and excitations that greatly affect peak motions, spectral content, and durations of shaking.

b. The great variation in the data that can occur locally for earthquake ground motions is superbly documented for the 1979 Imperial Valley, California, earthquake. Figures 6-3 and 6-4, from Singh (1985), show the spread that was recorded for peak particle acceleration, velocity, displacement, and duration for 0 to 15 km from fault surface rupture. The spread is nearly 400 percent, yet, the local area is about as uniform as one can expect to find anywhere in terms of site conditions, a large flat valley bottom filled with alluvium. With such variance at a uniform site, what will the variance be when sites are structurally and lithologically complicated? What happens when data from many sites are combined? Predictably, the range is several orders of magnitude. The sites for which motions are to be specified must be appraised in terms of such data.

c. For site appraisals there are approaches that are based on statistical distributions of data and on theoretical methods that utilize wave propagation theory.

(1) Use empirically derived magnitude or intensity based earthquake ground motion curves: these are available for hard and soft sites. The ranges in values for motions are bracketed statistically (mean, mean plus one standard deviation (SD), two standard deviations, maximum observed motions). A level is selected that is consistent with the needs at a project. Ordinarily, a mean plus SD puts one in a safe position where conservatism is desired. If a structure presents no hazard to life and the owner is willing to take the risk in order to obtain a cost benefit, then the design level can be much lower. Thus, the selection of an appropriate level of conservatism must be made.

(2) Factors can be applied to modify rock outcrop motions obtained above or to their response spectra to determine approximations for soil behavior. Representative examples are found in Seed and Idriss (1983).

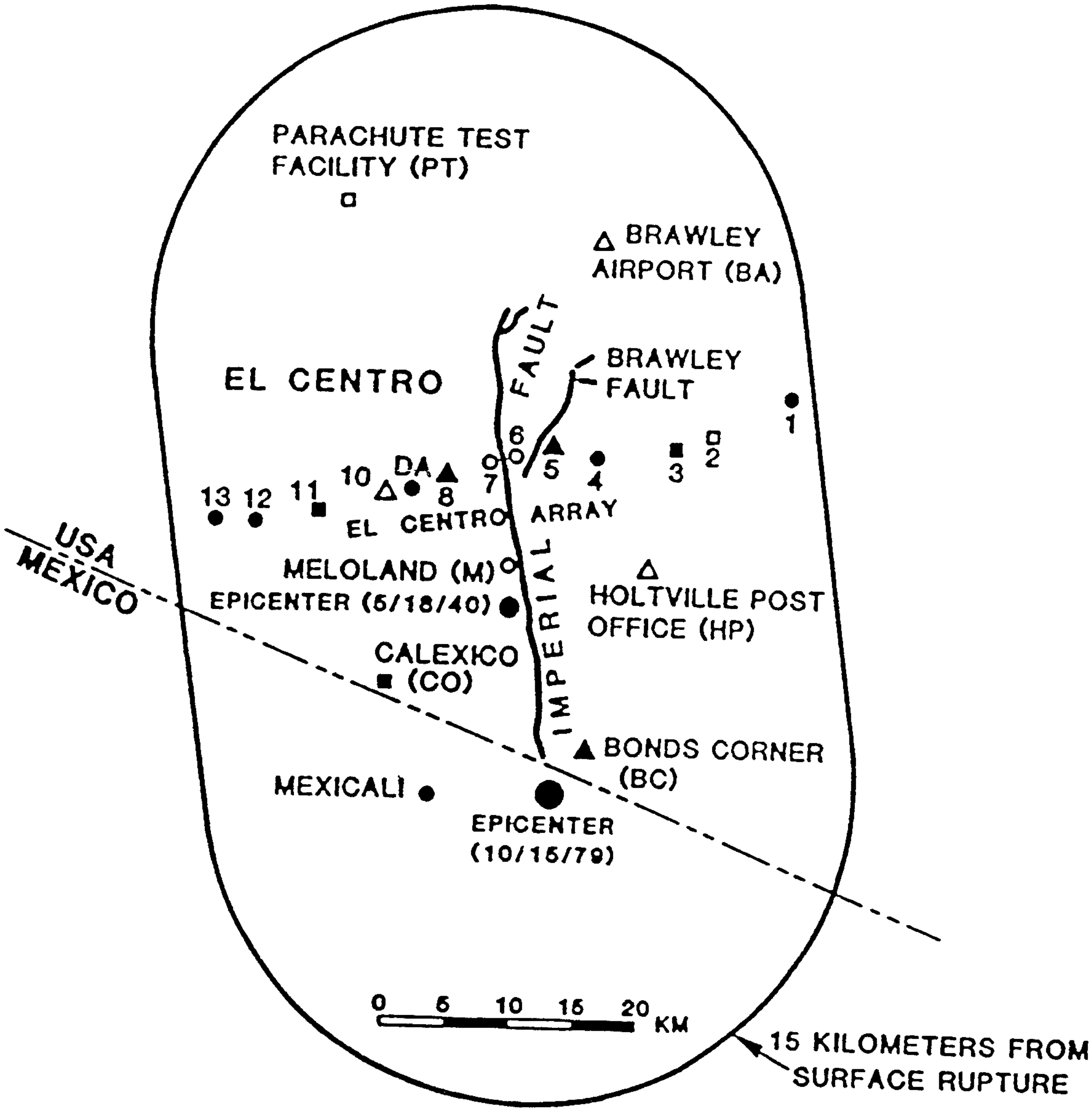
(3) Analyses are available in the forms of computer programs that take rock motions at the free field ground surface, deconvolute them to equivalent bedrock motion at depth, and utilize wave propagation theory with equivalent linear or nonlinear soil properties to calculate the motion at any desired depth in or at the surface of the soil above bedrock. Representative programs are SHAKE (Schnabel, Lysmer, and Seed 1972), WESHAKE (Sykora, Wahl, and Wallace 1992), DESRA-2 (Lee and Finn 1978), QUAD-4 (Idriss et al. 1973), and TARA-3 (Finn et al. 1986).

(4) Special studies are being made that examine amplification of seismic waves in shallow sedimentary basins of soft soils. Such situations may experience soil amplifications of 3-5X along with critical changes in the predominant period of excitation as happened in Mexico City during the 1985 earthquake. Still other effects are those of focussing of seismic waves in the direction of fault plane rupture (Bolt 1983). A critical project at which any of these influences might be present should consider a state-of-the-art examination for anomalous motions that are site dependent.

d. For general categories of *hard* and *soft* sites referred to in this manual and used for designating ground motion in Appendixes B and C, the boundary between *hard* and *soft* sites is taken at a shear wave velocity of 400 m/sec or 50 blow counts of the Standard Penetration Test at an overburden pressure of 1 kg/cm^2. The minimum thickness of a surface layer to define a soft site is 16 m.

6-8. Ground Motions in the Subsurface

a. Earthquake motions in the subsurface are greatly attenuated from those at the ground surface. The very best information for approximating this effect was obtained in China during the Tangshan Earthquake of 1976 and was reported by Wang (1980). The earthquake, of magnitude 7.8, was centered in Tangshan. Beneath Tangshan was a maze of shafts and drifts from coal mining that extended in the subsurface to a depth of 800 m. Fault displacements occurred within the areas that had been mined and an underground fault displacement resulting from the earthquake was measured at 1.2 m horizontal and 0.5 m vertical. Damage was observed on linings, masonry, and equipment throughout the mines and the effects of the earthquake shaking on people were noted. Wang's (1980) profiles of intensity in the mines are



STATION	SYMBOL	DISTANCE FROM SURFACE RUPTURE, KM
6,7,M	○	1
5,8,BC	▲	3
10,HP,BA	△	8
3,11,CO	■	11
2,PT	□	13
OTHER STATIONS	●	

Figure 6-3. Recording stations in the Imperial Valley, California, and epicenter of the 1979 Imperial Valley earthquake (Singh 1985)

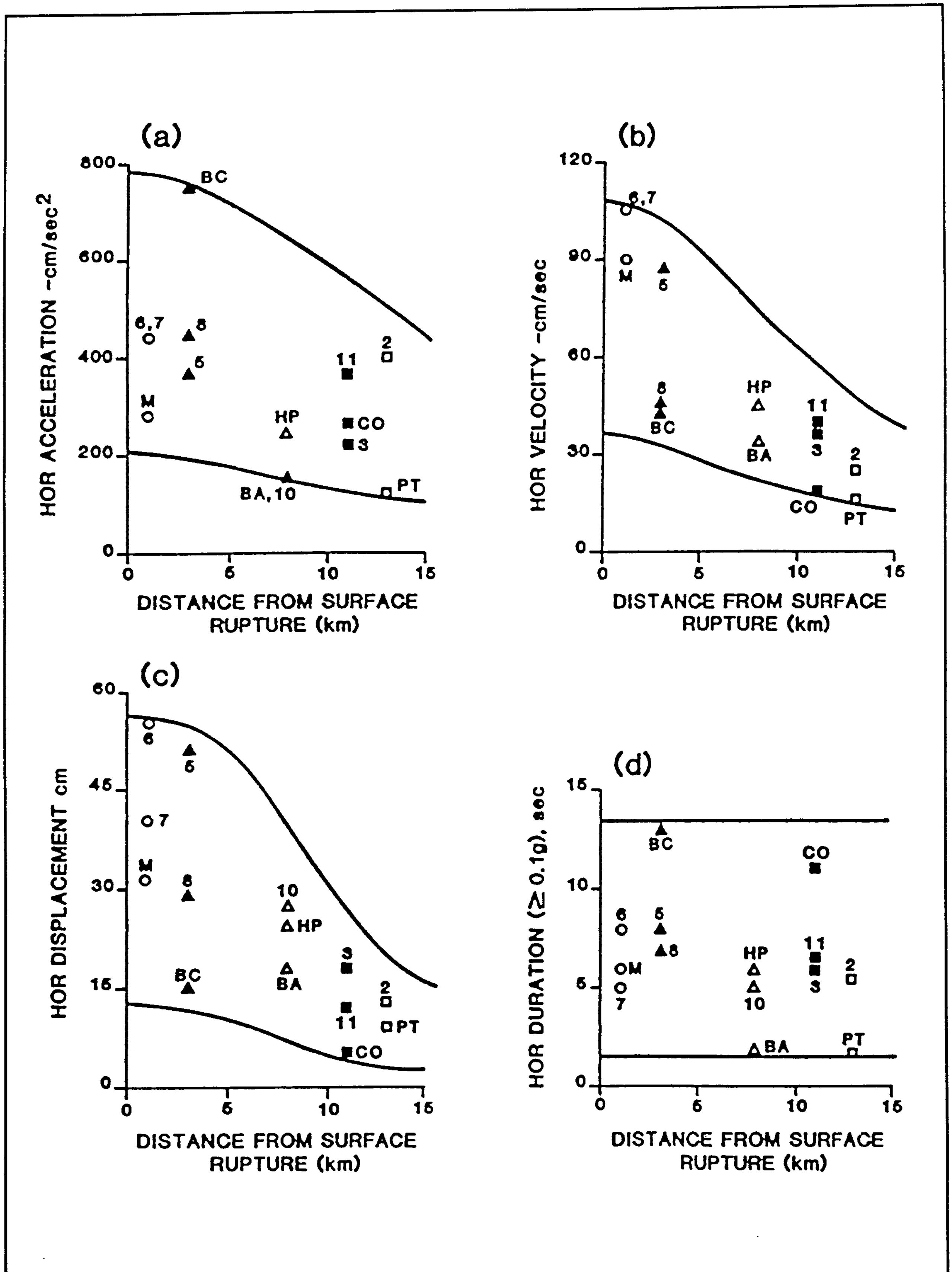


Figure 6-4. Ranges in peak motions with distance from surface rupture of the Imperial fault for the 1979 Imperial Valley earthquake (Singh 1985)

shown in Figure 6-5. He noted that there was a dropoff in intensity with depth down to a certain level beyond which the intensity remained constant. At Tangshan this depth was between 500 and 600 m. On this basis he developed a general equation as follows:

$$I = Ke^{-bh} + K_o$$

where

I = intensity (Chinese scale or MM scale)

K_o = constant subsurface intensity (K_o = 7 at Tangshan)

K = increase from constant intensity to intensity at the surface (11 - 7 = 4)

b = attenuation coefficient (-0.03)

h = depth, meters

For Tangshan:

$$I = 4e^{-0.03h} + 7$$

b. To assign peak ground motions for the intensities, the Krinitzsky-Chang charts in Appendix B should be used.

6-9. The Concept of Effective Motions

a. High peak ground motions have been recorded during moderate earthquakes. Table 6-1 is a listing of earthquakes that have had the severest horizontal motions. While the earthquake magnitudes are 5.4 to 6.6, the accelerations are 1 g or greater. When they result from very high frequency components of motion that cause no damage, because the frequency is well above the fundamental modes of the structures of interest, then lower motions are more appropriate for design. These situations usually occur at sites near a fault source. In a dynamic analysis these effects are automatically accommodated in the analysis if the time history is chosen properly. However, problems may result from scaling of so-called analogous records when such records are not chosen for appropriate high frequency peak motions. Additionally there are factors that are not routinely evaluated in the dynamic analyses, such as the patterns of wave incidence across a loaded area.

b. In practice, many important engineering projects, for which very high peak ground motions were proposed, have had their peak motion amplitudes reduced to achieve *effective* motions. These include the Trans-Alaska Pipe Line and various nuclear power plants (for a discussion, see Krinitzsky, Gould, and Edinger 1993). In practice, effective motions are an engineering decision for which there are no generally accepted procedures.

6-10. Near Field and Far Field Motions

In the *near field*, complicated reflection and refraction of waves occur with resonance effects and mismatches that produce a large variation in the values for ground motions. In the *far field* the wave patterns become more orderly and more muted. The extent of the near field varies with the size of the earthquake. Table 6-2 presents

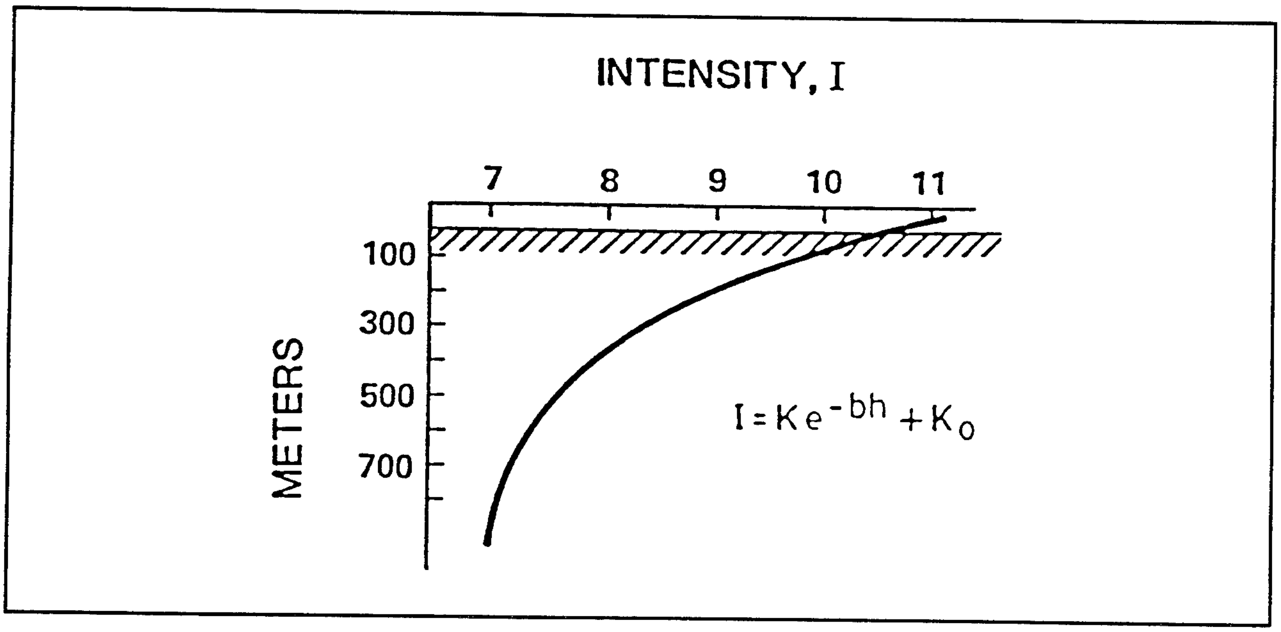


Figure 6-5. Changes in intensity with depth for the Tangshan earthquake of 1976 (Wang 1980)

Table 6-1
Horizontal Strong Motion Records 1 g or Greater

Earthquake	Hor Accel, g	Fault Dist, km	Mag M
Cerro Prieto (1987)	1.45	(At Site?)	5.4
Morgan Hill - Coyote Dam (1984)	1.29	(At Site?)	6.1
San Fernando - Pacoima Dam (1971)	1.25	4	6.6
Nahanni - Site 1 (1985)	1.25	(At Site)	6.6
Coalinga - Anticline Ridge (1983)	1.17	7.6	6.5
Transmitter Hill	0.96		
Palm Springs - Devers Substa. (1987)	0.97	(At Site)	6.0

Table 6-2
Limits of the Near Field. From Krinitzsky and Chang (1988).

Magnitude M	Modified Mercalli Intensity I_0	Maximum Distance From Sources km
5.0	VI	5
5.5	VII	5
6.0	VIII	25
6.5	IX	35
7.0	X	40
7.5	XI	45

distance limits for the near field. The values are applicable everywhere in both plate boundary and intraplate areas, because in the near field the effects of regional attenuations are not controlling determinants for the motions.

6-11. Parameters for Intensity-Related Motions

a. Appendix B presents a set of twelve charts that provide parameters for earthquake ground motions based on Modified Mercalli intensity. These charts are from Krinitzsky and Chang (1988). The charts include values for hard and soft sites, near field versus far field, and the sizes of earthquakes affecting durations. The curves are for mean values of motion and mean plus one standard deviation.

b. The proper predominant period will be obtained usually by selecting accelerograms that are appropriate for the site. For conservatism, an investigator may include records that have predominant periods like those of the structure under evaluation at the appropriate strain level. The data sheets in the report by Krinitzsky and Chang (1987) show predominant periods.

c. The charts present horizontal peak motions. Vertical motions can be obtained at 2/3 the horizontal or from the data sheets by Krinitzsky and Chang (1987).

d. The separation into near field and far field motions and the values given for duration make the Krinitzsky and Chang curves different from intensity curves by other authors. Thus the Krinitzsky and Chang curves cannot be compared to other curves.

6-12. Parameters for Magnitude-Related Motions

a. Appendix C presents a set of charts that relate parameters for earthquake ground motions to magnitude (M) of earthquake, hypocentral distance from the earthquake source, hard and soft sites, the shallow plate boundary with focal depths $\leq$ 19 km, and the subduction zone with focal depths $\geq$ 20 km. The curves are for mean values of motion, and mean plus one standard deviation.

b. An examination of the effects of type of fault movement on motion showed that corrections for type of fault generally were not warranted.

c. The curves are for use in areas of plate boundaries. In a plate interior, east of the Rocky Mountain front, where attenuations are distinctly different, the curves need to be altered for attenuation in the far field. In the near field, the curves can be used everywhere, the intraplate as well as the plate boundary.

6-13. Deterministic Seismic Hazard Evaluations

a. Deterministic seismic motions are obtained from a combination of empirical knowledge, theoretical conceptualization, and professional judgment but are not time dependent, meaning the motions are independent of the time interval of recurrence, or the probability. Procedures for obtaining deterministic motions are given in Chapter 7.

b. This report recommends that only the deterministic procedures be used for seismic hazard evaluations where critical structures are to be designed for maximum credible earthquakes in seismically active areas.

c. The probabilistic method may be used for operating basis earthquakes when an analysis is for a critical structure in a seismically active area. When the analysis is for a noncritical structure, implying a generalizing and relaxing in the criteria, or a critical structure in an area of low seismic threat, the probability values commonly suffice for all that is needed in design. Those values may be obtained from probability-based maps and do not require individual probabilistic assessments.

d. It is appropriate in study for a critical site to use the deterministic analysis to obtain motions for maximum credible earthquakes and to use available probabilistic maps to assign motions for an operating basis earthquake.

6-14. Probabilistic Seismic Hazard Evaluations

a. Seismic probability theory described in Appendix D assumes that no structure is absolutely safe and no motion is absolutely the maximum. Therefore, it is reasoned a probabilistic analysis is needed both to estimate the recurrence of whatever motions are assigned and, by projection, the larger motions that will occur over, commonly, as much as 10,000 years in the future. The problem is that there is a large body of evidence which shows these assumptions are not valid. Krinitzsky (1993) finds that the defect is in the Gutenberg-Richter b-line which is the earthquake magnitude and recurrence relation on which seismic probability is based. The Gutenberg-Richter b-line is dysfunctional for engineering because of differences in the mechanisms of faulting and nonuniformity in the occurrences of earthquakes over time and space. The mechanisms of faulting included stick slip, various categories of controlled slip, and a multitude of thermodynamic slip processes which range from rock melting and lubricated fault movements to stress releases by hydrothermal and other fluids at or near lithostatic pressures. These processes, and the effects of asperities and barriers along faults, contribute to a nonuniformity, or clustering, that both dominates earthquake occurrences and prevents characteristic earthquakes from having continuity through time. The b-lines must incorporate these complex and varied effects, but they can do so only when they are inclusive for large, seismically active areas such as southern California, the Aleutian arc, etc. Within the relatively small earthquake source areas and the specific earthquake sources that are critical to individual engineering sites, the b-lines become dysfunctional at $M \geq 5.0$. Because b-lines are the determinants of probabilistic seismic hazard analyses, there are severe restraints on the usefulness of probabilistic methods to assign earthquake ground motions for engineering.

b. Despite the defects cited above, there will always be a strong call for some probability values because they are desirable for decision making. There may be reasons to use probability estimates the way 100-year floods are used which also are irregular and uncertain. There are also risk analyses that are important in the making of engineering decisions for defensive measures in design and construction. For those purposes probability may be used. Probabilistic motions may be obtained either from maps (Algermissen et al. 1990) or from any of several computer programs (see Appendix D). However, maximum credible earthquakes for critical structures in areas of serious seismic threat should at the same time be site specific and deterministic rather than probabilistic.

6-15. Evaluating Seismic Risk

Risk analysis takes seismic probability into a perspective that combines it with risks from other major hazards at an engineering site. These hazards are given values for losses should they produce failures and the losses are coupled with the costs of corresponding defensive measures. The exercise, even with the weaknesses of the probabilistic method, can be enormously important for the planning of engineering construction because it compares relative rather than absolute behaviors. By keeping all factors within the time frame of the life of an engineering project, the procedure may be reasonably dependable for comparative purposes. A procedure for risk analysis was developed by Hynes and Franklin (In Press). The steps that they describe are shown schematically in Figure 6-6 and are as follows:

a. Identify damaging loads that may be applied unexpectedly to the structure and estimate probable times for the occurrences.

b. On the basis of annual probability of failure, establish the costs of construction needed for defensive designs.

c. Estimate expected losses due to failure versus initial construction cost for protection against seismic events.

d. Present the trade-off of expected losses against costs of construction. Express as incremental increase in initial construction cost to avoid incremental increases in potential losses.

6-16. Recommended Accelerograms and Response Spectra

Appendixes B and C show catalogue numbers for accelerograms that are recommended for the corresponding earthquake ground motions. The accelerograms and response spectra are listed by Leeds (1992). The records can be scaled to fit the appropriate curves and Leeds provides scaling factors for each record. Relationships are presented for all magnitude and intensity curves.

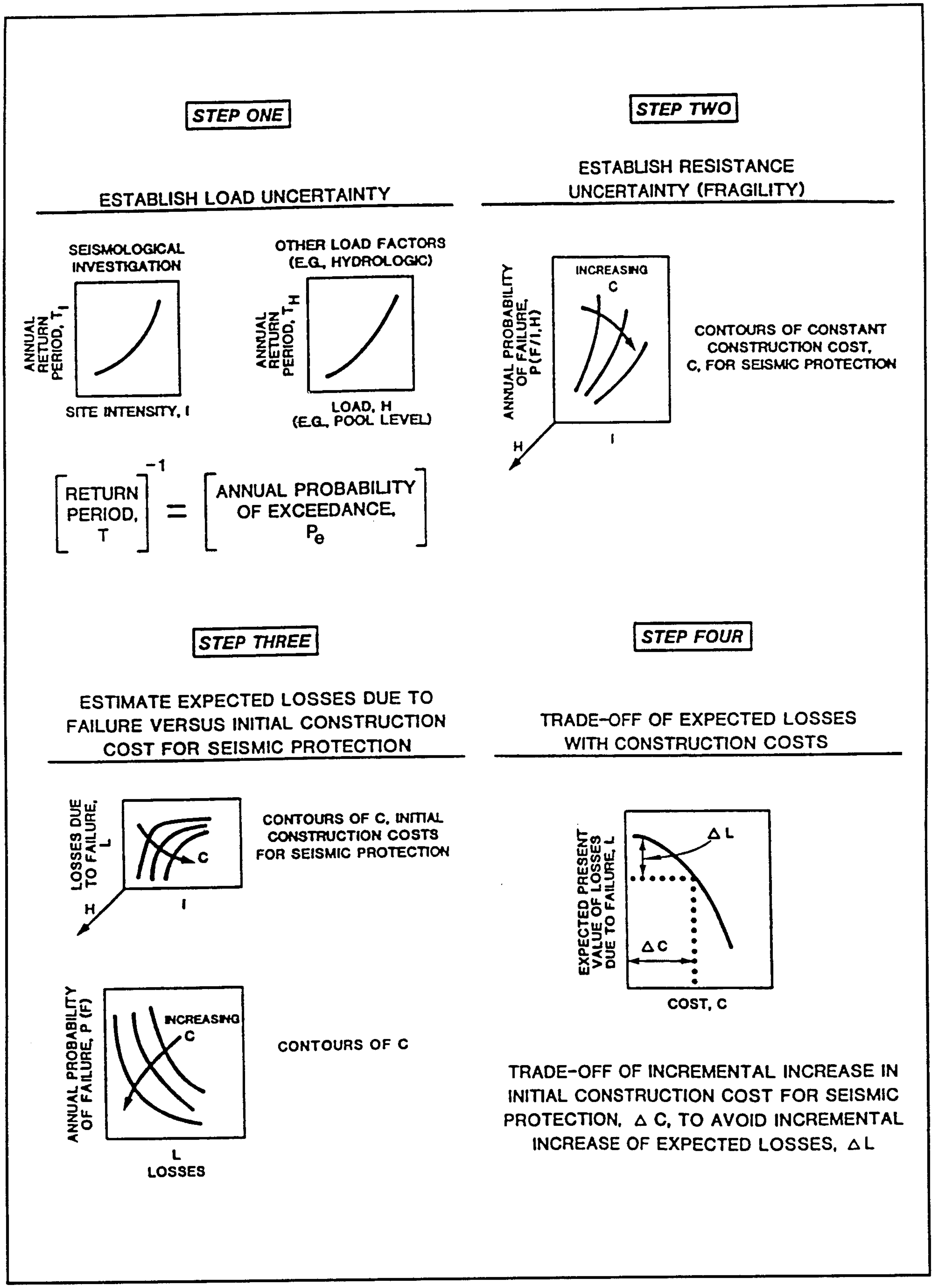


Figure 6-6. Procedure of Hynes and Franklin (in press) for risk assessment at an engineering project

Chapter 7
Procedures for Specifying Earthquake Ground Motions

7-1. Introduction

a. This chapter organizes the criteria presented in the preceding chapters and develops recommended procedures for assigning site-specific earthquake ground motions for engineering. These motions basically are those of the Maximum Credible Earthquake (MCE) and the Operating Basis Earthquake (OBE).

b. The MCE is the largest earthquake that can reasonably be expected. It is not the largest earthquake that is conceptually possible. The conceptual limit is something of an M = 9.7, but this is an extreme that need not be expected and, were it to happen, it would signify a fault rupture of 1,000 km or more but the shaking at any engineering site along or near the fault would have a saturation of peak motions comparable to M = 7.5 to 8.0.

c. Figure 7-1 compares the MCE with the OBE and lists the requirements and categories of data that are appropriate for each. Note that damage for the MCE is allowed so long as there is life safety. In a dam, rupture or breakage with strong leakage can be permitted so long as there is a design which throttles the outflow and prevents it from turning into catastrophic flooding.

d. The OBE is a lesser earthquake and should be one that can be expected during the life of the structure. Also, the structure should continue operating without interruption. The design level for this earthquake can be determined by economics so long as the constraints for operation and safety are satisfied. The OBE can replace the MCE for the design level of the structure if there is no hazard to life and there is a cost-risk benefit that the owner wishes to accept.

e. Both the MCE and the OBE require the same basic information. The extent of the investigation depends on decisions for the types of analysis to be performed or by regulatory code requirements. If accelerograms are required for a dynamic analysis, the earthquake sources, attenuations, site conditions, interpreted ground motions, spectra, and allowable response will very likely need to be examined. If coefficients are used in a pseudostatic analysis for a noncritical structure or for a critical structure where there is no seismic threat, no other input may be needed.

7-2. Effects of Criticality of Structures on Procedures

a. Figure 7-2 categorizes critical and noncritical structures by the question *are the consequences of failure intolerable*? This is a question that is answered in terms of hazard to life, severity of economic loss, and necessity for continuity of services. Major dams, power plants, hospitals, important defense installations, etc., should be regarded as critical.

b. When a structure is deemed to be *critical*, deterministic procedures should be used. The deterministic method is preferable also for the OBE; however, the years of the life of the structure are part of the definition, and there is latitude allowed in the formulation of OBE motions. For those reasons, general probabilistic motions which are available in published maps can be considered and used.

c. Note that motions based on MM intensity are preferred for central and eastern United States. In those areas, fault sources are elusive and the historic record is almost entirely in intensity. In the western United States, fault sources are often well defined and accelerogram records are plentiful so that attenuated motions for magnitude and distance from the fault source can be the more satisfactory approach. Seismic risk analysis is a comparative evaluation and need not be a determinant in design. It requires time-related associations and makes use of probabilities in a relative sense. Where it is used to set priorities, or for the selection of sites, its use is advantageous and can be justified. For noncritical structures, or for critical structures in those areas of low seismic threat (less than 0.15 g), deterministic procedures can be used and may be preferred for the MCE but they are relatively expensive and they may not be warranted because of limited concerns for seismic hazards. For these circumstances, analyses based on published maps of probabilistic ground motions can be used.

7-3. Effects of Strength of Earthquake on Procedures

If a structure is critical, the site does not necessarily require a thorough investigation. No extensive investigation is needed if the site can be shown to have a low seismic threat. Figure 7-3 gives guidelines that are in terms of the size of earthquake and distance from source. If the severest earthquake is less than M = 6.0 and its source is more than 25 km from a site, then a full

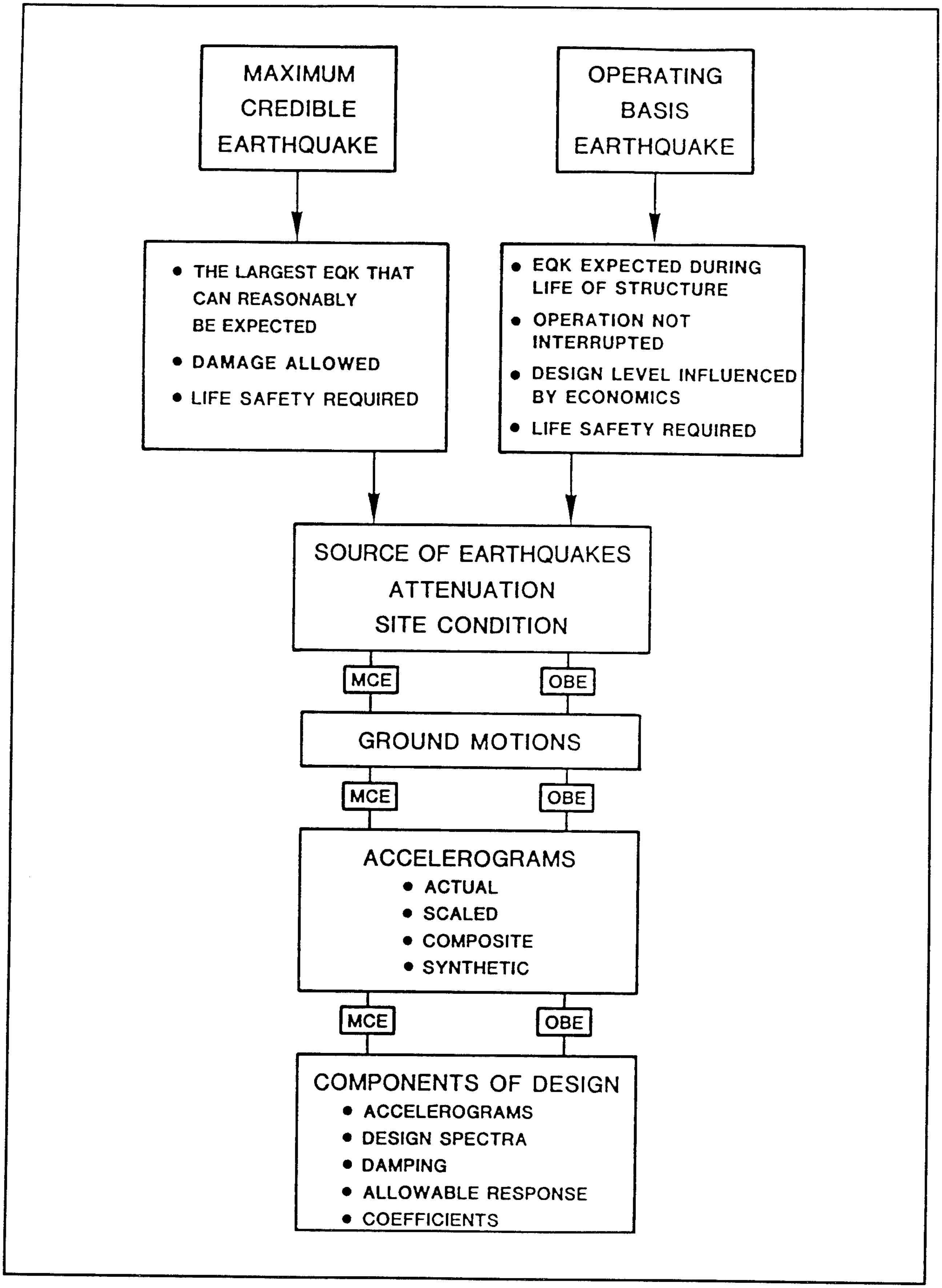


Figure 7-1. Characteristics of the Maximum Credible Earthquake (MCE) and the Operating Basis Earthquake (OBE)

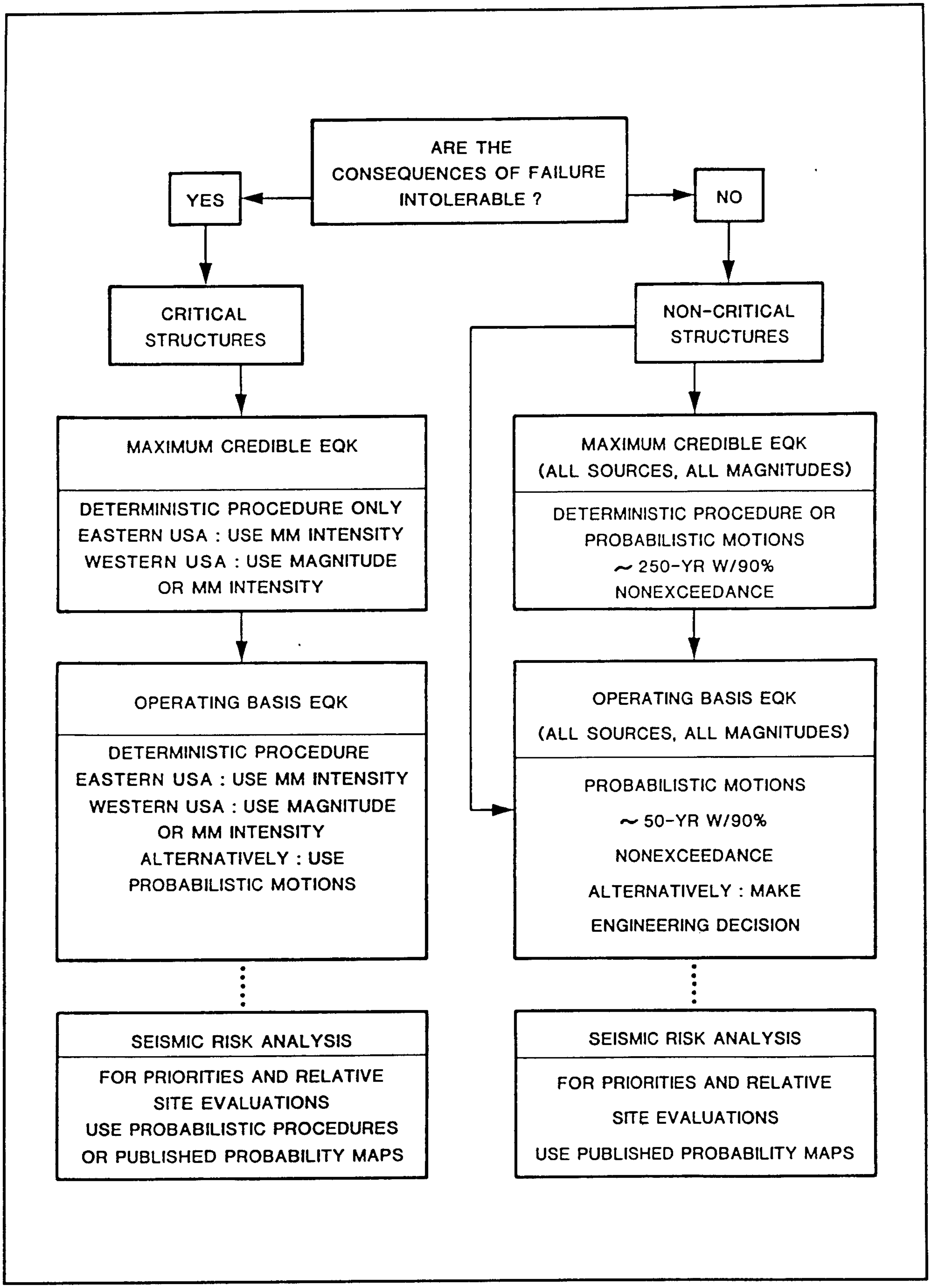


Figure 7-2. Procedures for determining MCE and OBE motions

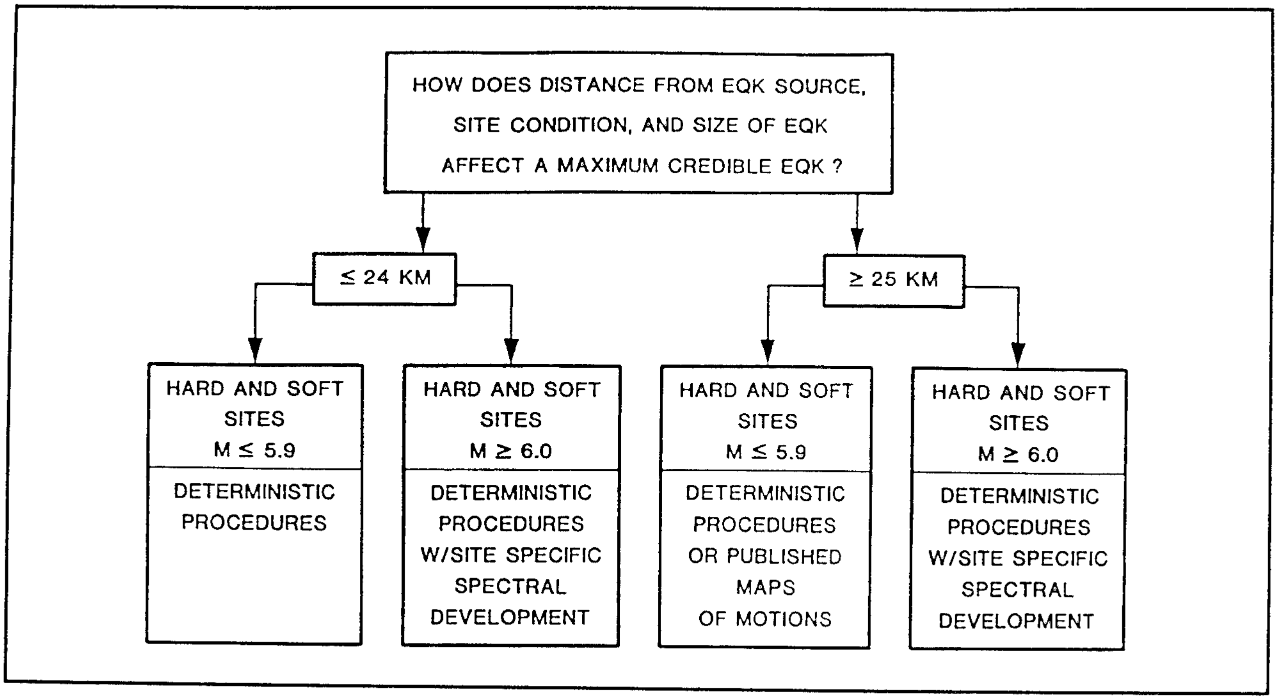


Figure 7-3. Effect of earthquake strength on selection of motions for an MCE at a critical structure

investigation is optional and should be performed only if there is a critical structure. Other structures can be evaluated by non-site-specific methods. Where earthquakes are greater than M = 6.0 and are likely to affect a site, a full site-specific investigation is in order.

7-4. Use of Geological and Seismological Information

a. The geological-seismological investigations are outlined in Figures 7-4 to 7-8. Their objectives are to:

(1) Locate the sources of earthquakes.

(2) Gather information on the type and character of faults that are capable of producing earthquakes.

(3) Designate seismic source zones where earthquakes occur but faults are not manifest at the surface.

(4) Specify magnitudes for earthquakes from these sources.

(5) Relate magnitudes to earthquake ground motions attenuated from the earthquake source to the engineering site.

(6) Provide analogous accelerograms and/or response spectra for engineering evaluations at the site.

b. Trenching at the site may be desirable to be certain that no faults exist beneath the proposed location for a structure. Should a fault be present, the structure can be moved a short distance so that the fault does not threaten to cause permanent displacements in the foundation.

c. If, as part of the field investigation, it is found that extensive trenching is required to determine the precise earthquake potentials for faults, the costs can be enormous and the results may still be uncertain. It can be practical to do no trenching but simply to take a worst case scenario for those earthquakes and see what the earthquakes produce in the way of motions at the site. If they make little or no difference in the design requirements, then this trenching can be eliminated. One needs to do only enough work to have a reliable and defensible design for the structure.

7-5. Investigations in Areas of Seismic Source Zones

a. Seismic source zones are inclusive areas that are designated for a given level of seismic hazard. Such zones are essential where there is seismicity but evidence of causative faults is lacking.

b. A maximum magnitude earthquake is postulated as able to occur anywhere in a seismic source zone. The

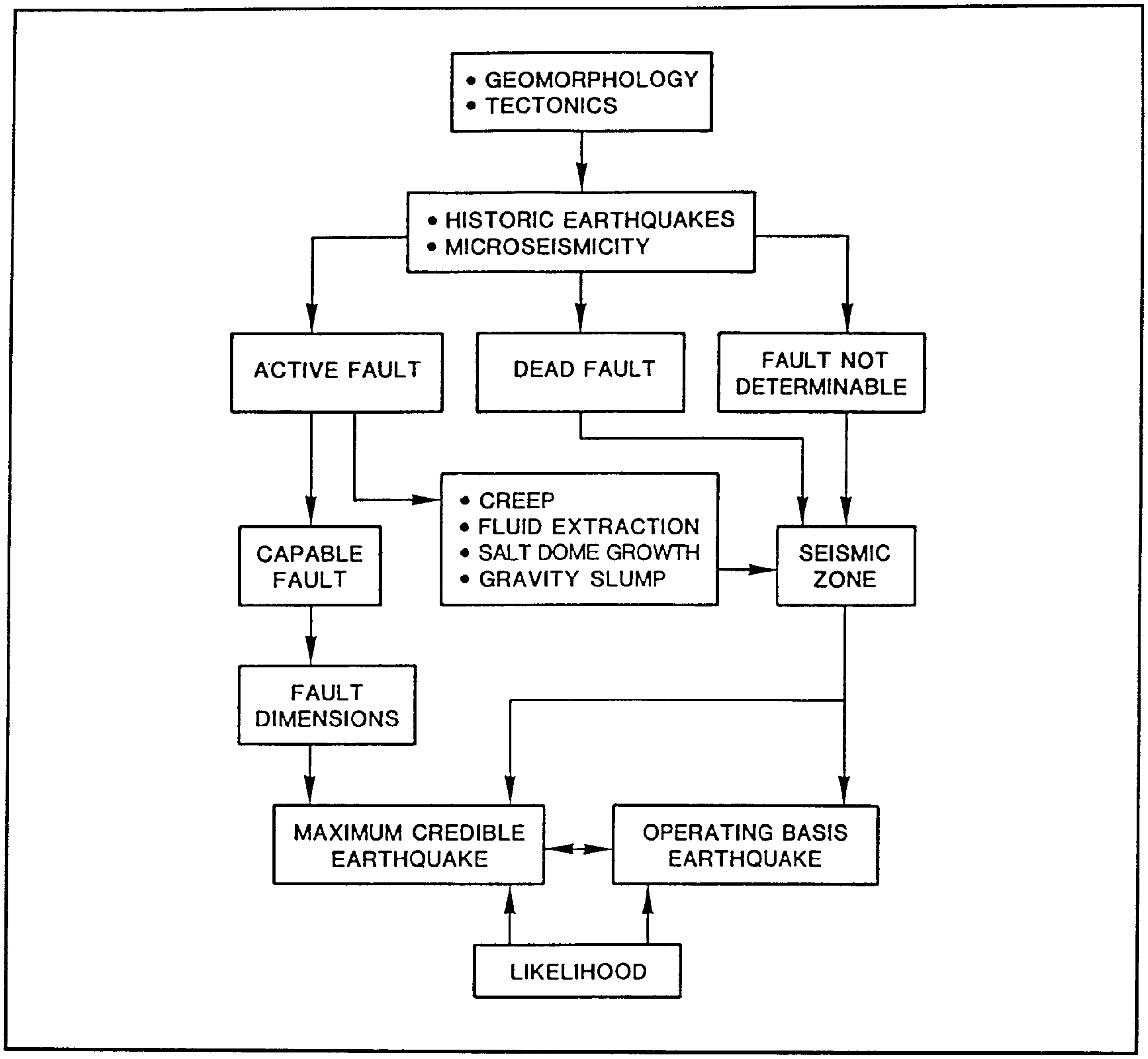


Figure 7-4. Geological and seismological factors in decisions for MCE and OBE

earthquake is a *floating earthquake*. A seismic zone is supplemental to, and can include, causative faults within the zone that have been identified as sources of earthquakes. The purpose of zones with floating earthquakes is to avoid surprises, particularly from capable faults that have not been mapped. Seismic zones usually do not coincide with tectonic or physiographic provinces since those provinces represent tectonism of the past. The seismic zone shows tectonism of the present. Seismic zones are determined by the patterns of observed earthquakes and the assigned maximum earthquakes within them are determined partly by the sizes of observed earthquakes and partly by corroborative geological evidences of earthquake activity.

c. Criteria for determining boundaries for seismic zones are described in Chapter 3. For seismic source zones, intensity-related earthquake ground motions are preferred means of evaluation. The procedure for assigning site-specific earthquake ground motions based on intensity is shown in Figure 7-6.

(1) The key to using intensity is to establish near-field and far-field source relationships.

(2) One must define the presence or absence of hotspots.

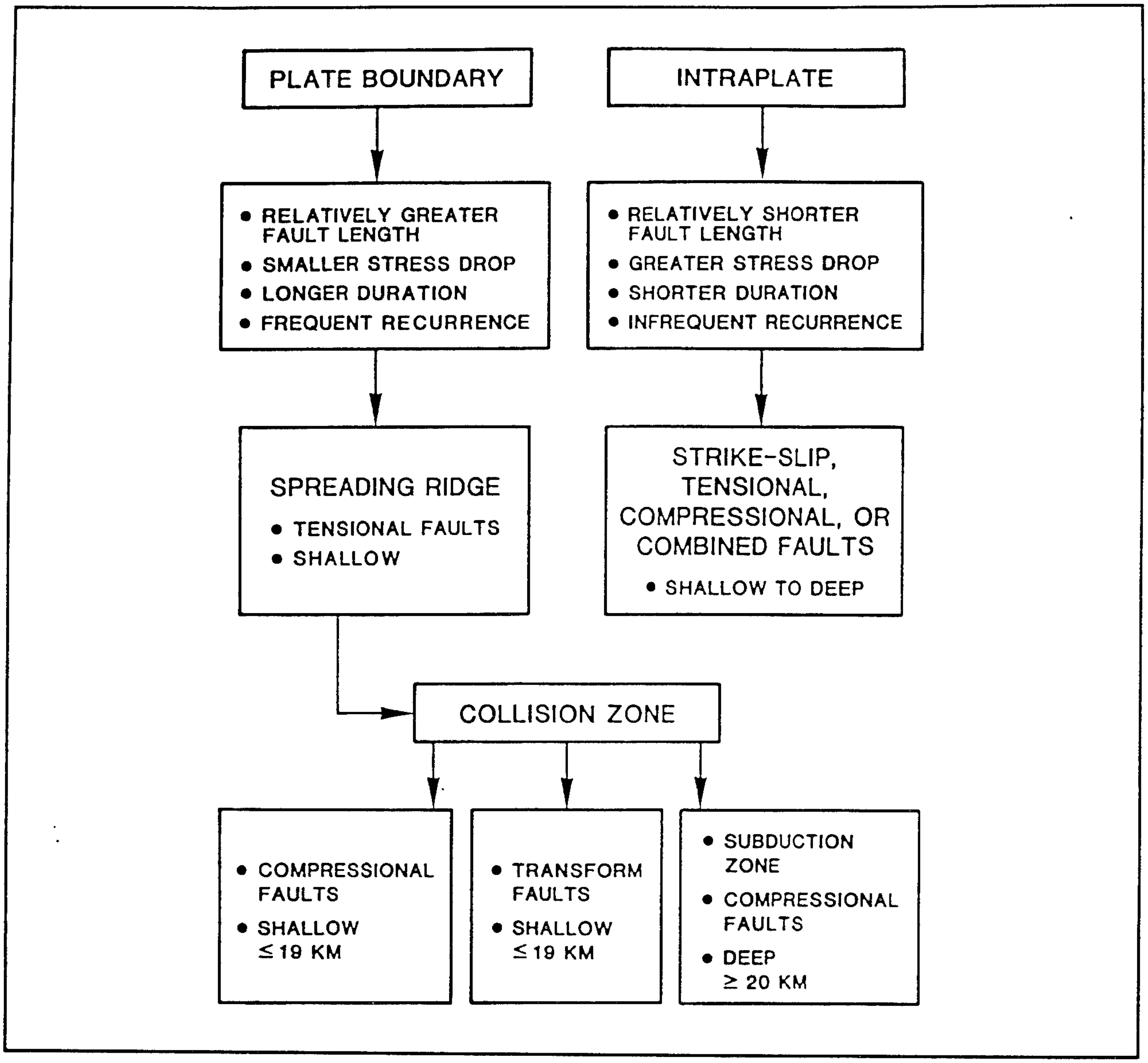


Figure 7-5. Comparison of plate boundary and intraplate processes on characteristics of earthquake sources

(3) Floating earthquakes require near-field motions when a site is in, or within near-field range of, a hotspot. With no hotspot, floating earthquakes are given far-field motions.

(4) Charts for horizontal earthquake ground motions based on Modified Mercalli intensities by Krinitzsky and Chang (1987) are provided in Appendix B. These intensity charts provide near-field and far-field motions.

(5) Intensity values can be used also for fault sources but they may not be as satisfactory as magnitude-related ground motions.

d. Example:

(1) The site is Gathright Dam in western Virginia. The location is shown in Figure 7-9. For a detailed report, see Krinitzsky and Dunbar (1990).

(2) Studies were made of

(a) Literature, for reports of recent tectonism, seismicity, and activity of faults.

(b) Aerial photography to identify faults and linears at the dam and in the vicinity.

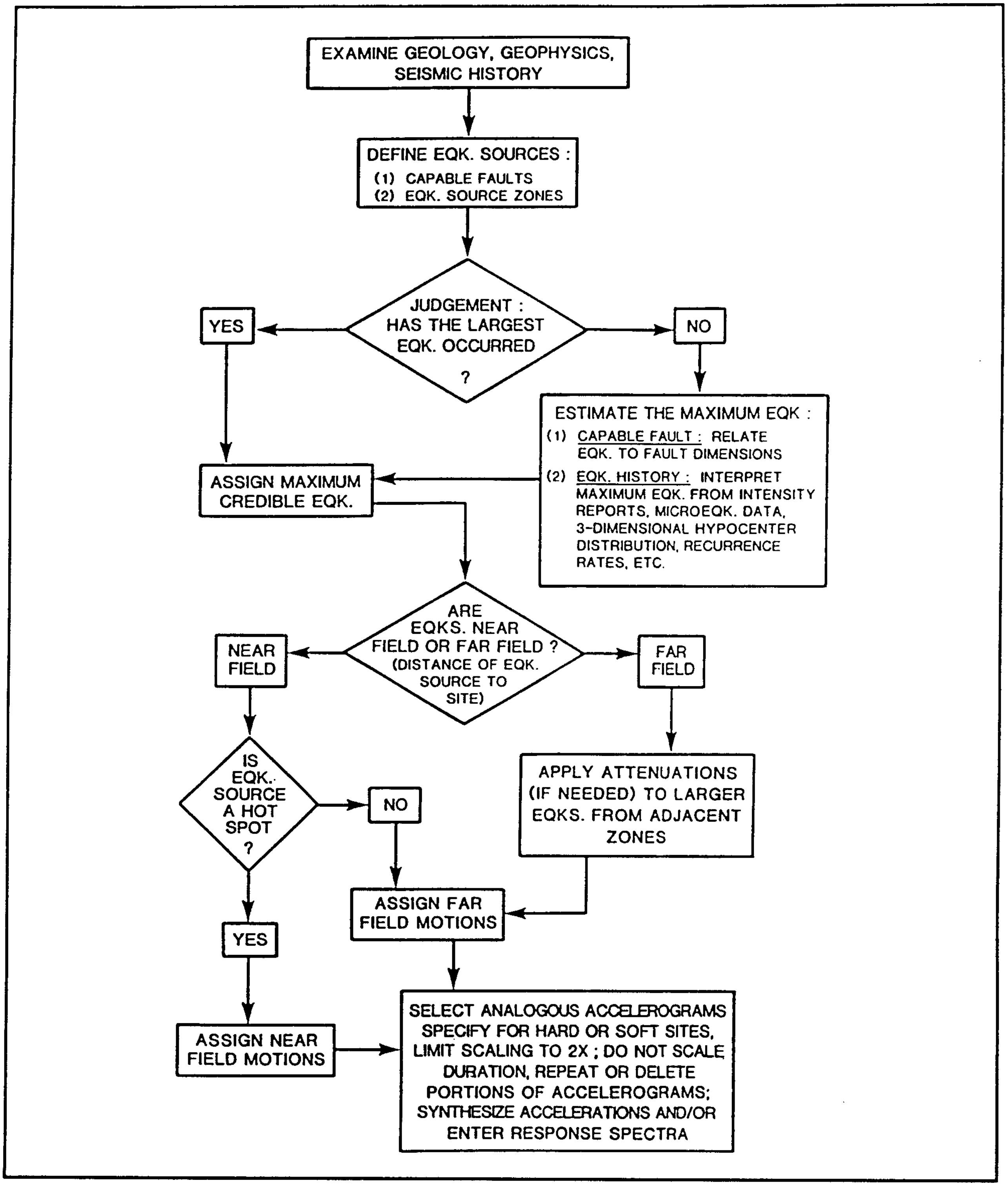


Figure 7-6. Procedure for generating intensity-related earthquake ground motions in all areas

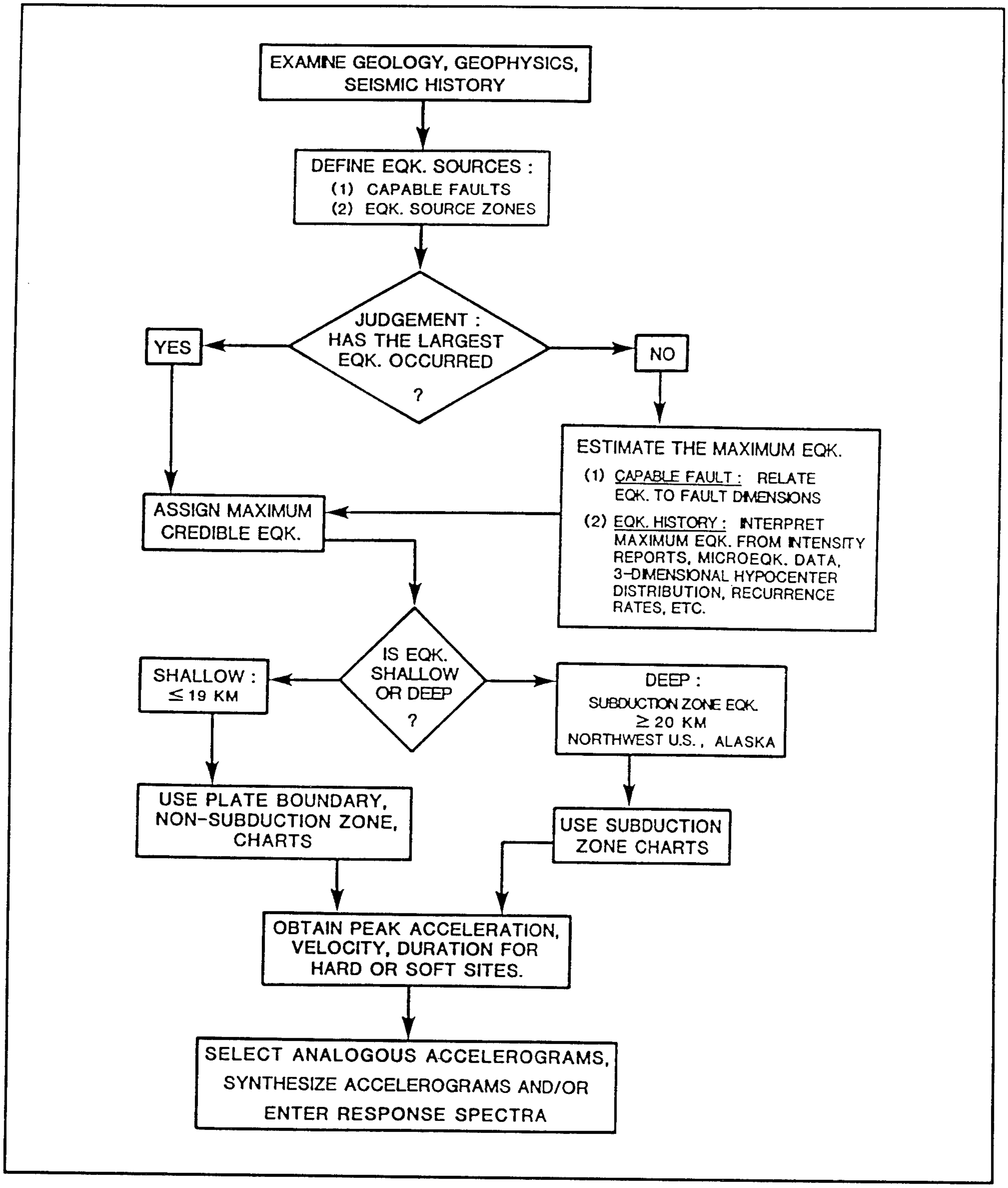


Figure 7-7. Procedure for generating magnitude-related earthquake ground motions in plate boundary areas

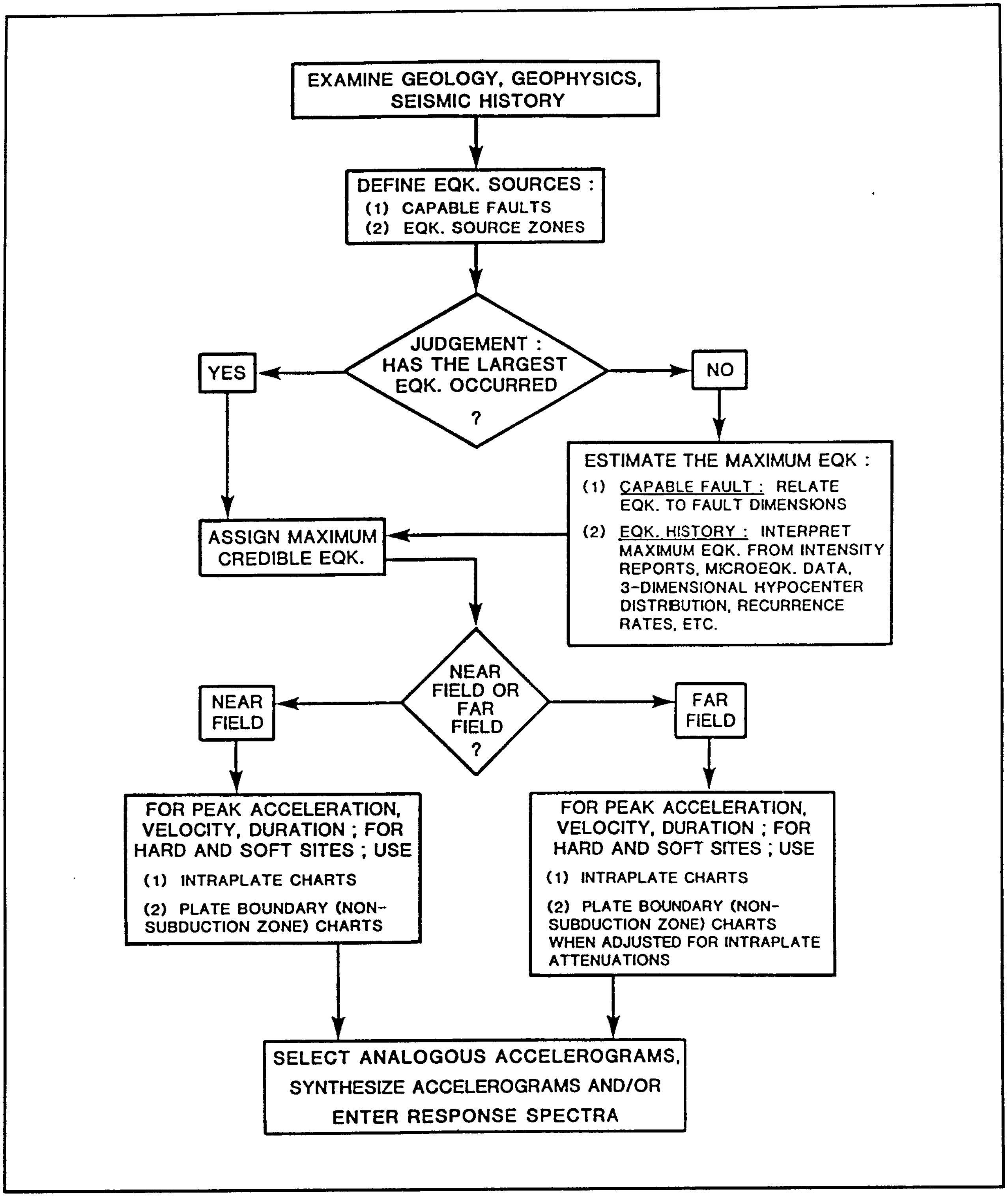


Figure 7-8. Procedure for generating magnitude-related earthquake ground motions in intraplate areas

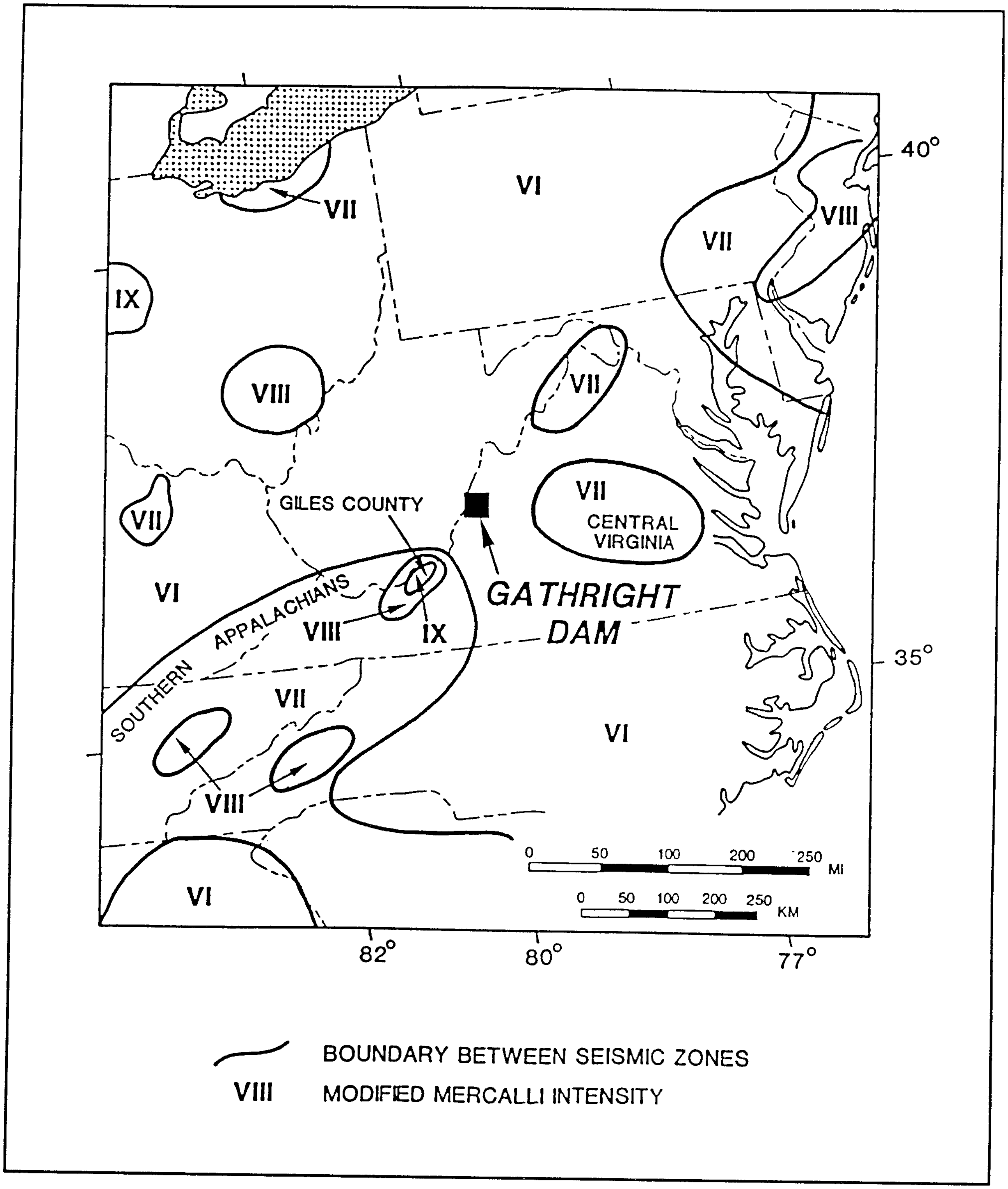


Figure 7-9. Location of Gathright Dam with interpreted seismic source zones

(c) Field studies.

(d) The historic record of seismicity.

Conclusion from the above studies: There are no active or capable faults in the project area.

(3) Gravity and aeromagnetic surveys were examined in combination with the geology and structure.

Conclusion: There are no anomalous geological structures at the damsite.

(4) Microearthquake monitoring was done at a hydroelectric project 16 km north of Gathright Dam between 1978 and 1982 and over the general area of both dams from 1978 to 1987. The monitoring covered the times of initial filling and several annual cycles of changes in reservoir levels. Microearthquakes at Gathright Dam and Reservoir were practically nonexistent. Concentrations of microearthquakes were in central Virginia and in Giles County (see Figure 7-9). Historic earthquakes during the period of 1774 to 1977 (prior to instrumentation) and microearthquakes since then show a close correspondence in source areas. The Giles County area experienced a dozen felt earthquakes, the greatest being on 31 May 1897 with MM intensity VIII. Microearthquakes combine in Giles County with the felt events to identify both a fault source and an actual fault plane. In contrast, the central Virginia source has a diffuse seismicity and it is low-level.

Conclusion: Giles County is identified as a seismic hot-spot 65 km from Gathright Dam. Central Virginia is a more diffuse seismic source at about the same distance.

(5) A maximum magnitude potential for earthquakes was determined for the Giles County fault-plane source by

(a) Seismic moment: $M_s = 6.6$

(b) A one-increment addition to the observed maximum: $M_s = 7.0$

(c) A Gutenberg-Richter magnitude-recurrence relation for 1,000 years normalized for 100,000 km^2: $M_s = 7.0$. Of the methods, the Gutenberg-Richter recurrence was judged to be unreliable in principle. The seismic moment was the most closely related evaluation of the seismic source. The seismic moment value was used to provide an equivalent MM IX for an MCE at the Giles County source. For the central Virginia source, MM VII was assigned as the MCE based on a single highest experienced event of MM VII of 23 Dec 1875.

(6) The OBE was given a 100-year occurrence at MM VI both locally at the site and attenuated from the Giles County and central Virginia sources using the Chandra (1979) attenuation for Eastern Province.

(7) The MCEs were attenuated from the sources to the site using Chandra. The dominant MCE at the Gathright Damsite was a far field MM VII from the Giles County source.

(8) Motions were assigned for a far field MCE of MM VII and a far field OBE of MM VI using curves for MM intensity and ground motions by Krinitzsky and Chang (1987, 1988). Values are given in Table 7-1.

Table 7-1
Assigned Motions for an MCE and an OBE

	Acceleration (cm/sec^2)	Velocity (cm/sec)	Duration sec ≥ 0.05 g
MCE for Giles County Source Hard Site, Far Field, MMIs VII, Peak Horizontal Motions			
Mean	130	9	5
Mean + SD	190	14	11
OBE for Central Virginia and Giles County Source Hard Site, Far Field, MMIs VI, Peak Horizontal Motions			
Mean	80	5	3
Mean + SD	125	8	3

Where vertical motions are desired, they may be obtained by taking 2/3 of the horizontal values. Time histories and response spectra can be fitted to these parameters.

(9) Accelerogram and response spectra suitable for the above parameters can be obtained from Appendix B and reference to Leeds (1992).

7-6. Investigations in Areas with Fault Sources

a. Procedures for obtaining site-specific earthquake ground motions from magnitude and distance relationships are described in Figures 7-7 and 7-8 for the fault-source area of western United States shown in Figure 3-3. Figure 7-7 refers to this plate-boundary area and includes the subduction zone. The important distinction is whether to use charts for shallow plate boundary or, if a subduction zone is present, for the deeper sources. When subduction zone charts are used, one must also use shallow plate boundary charts. Both sources will be operative together.

b. Figure 7-8 details the steps to be taken for an intraplate area:

(1) Plate boundary charts can be used without adjustment in the intraplate so long as the site is in the near field.

(2) For the far field, plate boundary charts must be altered to incorporate intraplate attenuations.

(3) Alternatively, other charts can be obtained that are developed specifically for the intraplate.

c. Magnitude and ground motion charts for use in the shallow plate boundary and in the subduction zone are contained in Appendix C. A caution is that no charts are satisfactory for very soft materials, such as the San Francisco Bay muds or the lake deposits of the Mexico City basin. Their peak motions and spectral content have to be analyzed and adjusted by the experiences observed in the San Francisco Bay area, Mexico City, and elsewhere. Criteria are being researched but at present there are no established procedures.

d. Example. The following is representative for an area with young surface faulting. For a more detailed account of the investigation see Krinitzsky (1989).

(1) The site is at the Tooele Army Depot, 25 km south of Tooele, UT. The structure is rated as critical. The location is in a valley of the Basin and Range Province in which there is an abundance of active normal faults near the site. Also, the site is 50 km from the Wasatch fault, a major active feature with a length of 350 km and capable of a world-class earthquake. Such an earthquake has not occurred in historic time, but the area has been settled only since 1847. For locations of the Wasatch fault and the local faults see Figures 7-10 and 7-11, respectively.

(2) A literature review was made on the following subjects:

(a) Trenching and interpretation of seismic events along the Wasatch fault.

(b) Geology and tectonism in the Tooele Valley.

(c) Seismic history.

(3) A field reconnaissance was made of faults in Tooele Valley. Faults were found to occur throughout the valley. Scarp morphology confirmed that the faults were numerous, young, capable of producing severe earthquakes, and were situated close to the site.

(4) The seismic history between 1894 and 1981 within 150 km of the site includes 24 earthquakes of $m_b \geq 4.5$ and MMI $\geq$ VI. The maximum MM intensity was VIII. Because of the short seismic history, the maximum earthquake potential must be determined from the faults through geological investigation.

(5) Trenching found active faults at the construction site. The site was moved a short distance to avoid the possibility of permanent displacements developing in the foundation from fault activation.

(6) Field evidence showed that *en echelon* groupings of faults in Figure 7-10 have the following potentials:

(a) The faults in a zone would be capable of all moving at the same time. This assumption is based on field evidence by which these faults were seen to have moved together in their respective zones in the past.

(b) Different zones have not moved together with each other during the Quaternary. Again, the basis is in the field evidence.

(c) Movement of about 4 m represents the maximum for a single event. Northern Oquirrh and Stansbury were the sources of these maximum individual movements. They represent fault lengths estimated minimally at 17 and 14 km, respectively.

(d) Saint John Station represents faulting in the midvalley. Valley fill at this site is somewhat under 1,000 ft thick. Fault movement would have been initiated in the rocks beneath the valley fill and the displacement would have been transmitted through this thickness of unconsolidated materials. In order to be manifest, the midvalley faults must have bedrock displacements that are appreciable though the dimensions are indeterminant.

(e) Recurrence times were not determinable.

(7) On the basis of fault lengths and displacements, two maximum values for a local earthquake affecting the project site were assigned. They are sources in the Stansbury and Northern Oquirrh zones with M = 7.5 at 21 km, and the Mercur zone with M = 7.0 at 4 km.

(8) Published studies from trenching along the Wasatch fault indicated individual fault displacements of 1.6 to 2.6 m and an average displacement of 2 m. The number of segments along the length of the Wasatch fault that would move individually during earthquakes has been estimated at 6 and 10. For a total length of the Wasatch fault of about 350 km, lengths that move during an earthquake can vary from 35 to 58 km. A range of M = 6.5 to 7.8 is indicated. Displacement of 2.6 m indicates an M = 7.5. An M = 7.5 is assumed. The site is 50 km from the nearest point on the Wasatch fault.

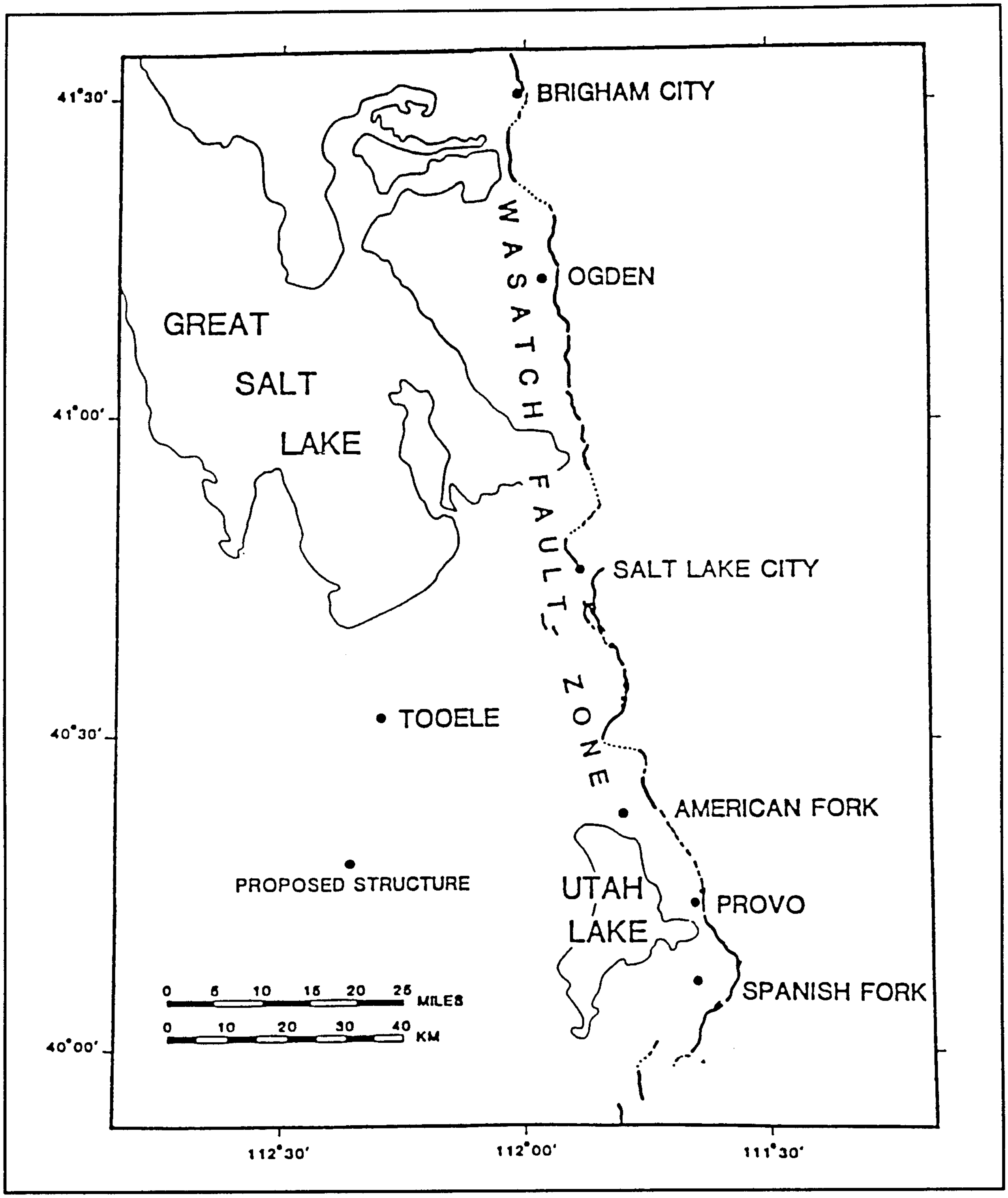


Figure 7-10. The Wasatch fault zone in relation to the construction site

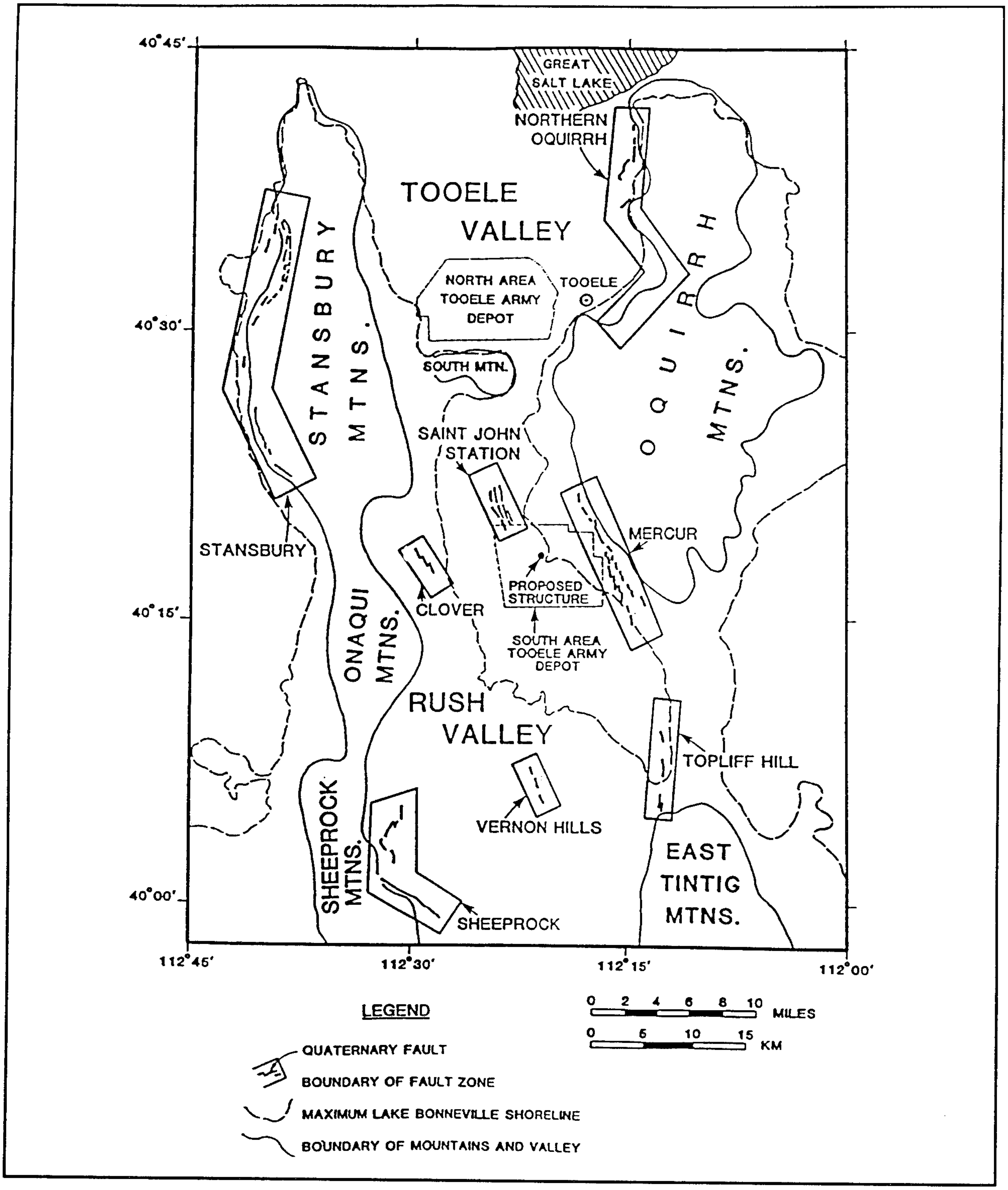


Figure 7-11. Areas of Quaternary faulting in the vicinity of the Tooele Army Depot

(9) The local earthquake source, M = 7.5 at 21 km, provides peak horizontal acceleration values as shown in Table 7-2.

Table 7-2
Peak Horizontal Acceleration

Earthquake Motion Charts	Peak Horizontal Acceleration, cm/sec², Hard Site Mean	Mean + SD
Krinitzsky and Chang (1987) (Intensity)	1,200	1,200
Krinitzsky, Chang, and Nuttli (1988) (Magnitude)	580-650	1,100-1,200
Joyner and Boore (1981) (Magnitude)	300-500	400-1,100
Campbell (1981) (Magnitude)	420	440-800
Seed and Idriss (1983) (Magnitude)	370-620	540-900

(10) Table 7-3 lists peak horizontal motions recommended for the local maximum credible earthquake, from the magnitude and distance charts by Krinitzsky, Chang, and Nuttli (1988):

Table 7-3
Peak Horizontal Motions Recommended for Local MCE

Site	Acceleration cm/sec²	Velocity cm/sec	Duration (≥ 0.05 g) sec
Hard	Mean	580	4213
Hard	Mean + SD	1,100	7218
Soft	Mean	580	10037
Soft	Mean + SD	1,100	18054

(11) Table 7-4 is a comparison of peak horizontal acceleration for a Wasatch maximum credible earthquake.

Table 7-4
Peak Horizontal Acceleration for a Wasatch MCE

Earthquake Motion Charts	Peak Acceleration, cm/sec², Hard Site Mean	Mean + SD
Krinitzsky and Chang (1987) (Intensity)	180	280
Krinitzsky, Chang, and Nuttli (1988) (Magnitude)	200	380
Joyner and Boore (1981) (Magnitude)	90	200
Campbell (1981) (Magnitude)	150	230
Seed and Idriss (1983) (Magnitude)	190	280

(12) Krinitzsky, Chang, and Nuttli (1988) magnitude and distance values for a Wasatch maximum credible earthquake are listed in Table 7-5.

Table 7-5
Magnitude and Distance for a Wasatch MCE

Site		Acceleration cm/sec²	Velocity cm/sec	Duration (≥ 0.05 g) sec
Hard	Mean	200	16	13
Hard	Mean + SD	380	26	18
Soft	Mean	200	33	39
Soft	Mean + SD	380	58	56

(13) For an operating basis earthquake which should be an event that could happen during the life of the structure, the historic earthquakes in the area show five of MM VII and one of MM VIII during almost a century. MM VII could be taken as the 100-year earthquake for the area and the event would be far field. Peak horizontal motions for an operational basis earthquake, from Krinitzsky and Chang (1987) intensity and motion curves are shown in Table 7-6.

Table 7-6
Peak Horizontal Motion for an OBE

Site		Acceleration cm/sec²	Velocity cm/sec	Duration (≥ 0.05 g) sec
Hard	Mean	133	8	5
Hard	Mean + SD	180	14	12
Soft	Mean	133	14	5
Soft	Mean + SD	180	20	12

(14) Accelerograms and response spectra suitable for the above parameters can be obtained from Appendix B and reference to Leeds (1992).

7-7. Probabilistic Assessment

a. Figure 7-12 details the steps that are followed in generating probabilistic seismic hazard evaluations. Seismic probability is discussed in greater detail in Appendix D.

(1) As discussed previously, seismic probability theory has a conceptual flaw in the reliance it places on b-lines. For large earthquakes, the ones that can cause damage to engineered structures, the time-dependent b-line interpretations are of questionable reliability.

(2) Probabilistic seismic values are suitable for structures when they are located in areas of very low seismic threat. Published maps of probabilistic seismic motions (Algermissen et al. 1990) are sufficient for those purposes.

(3) When risk analyses are needed for priorities or relative site evaluations, site-specific probabilistic studies

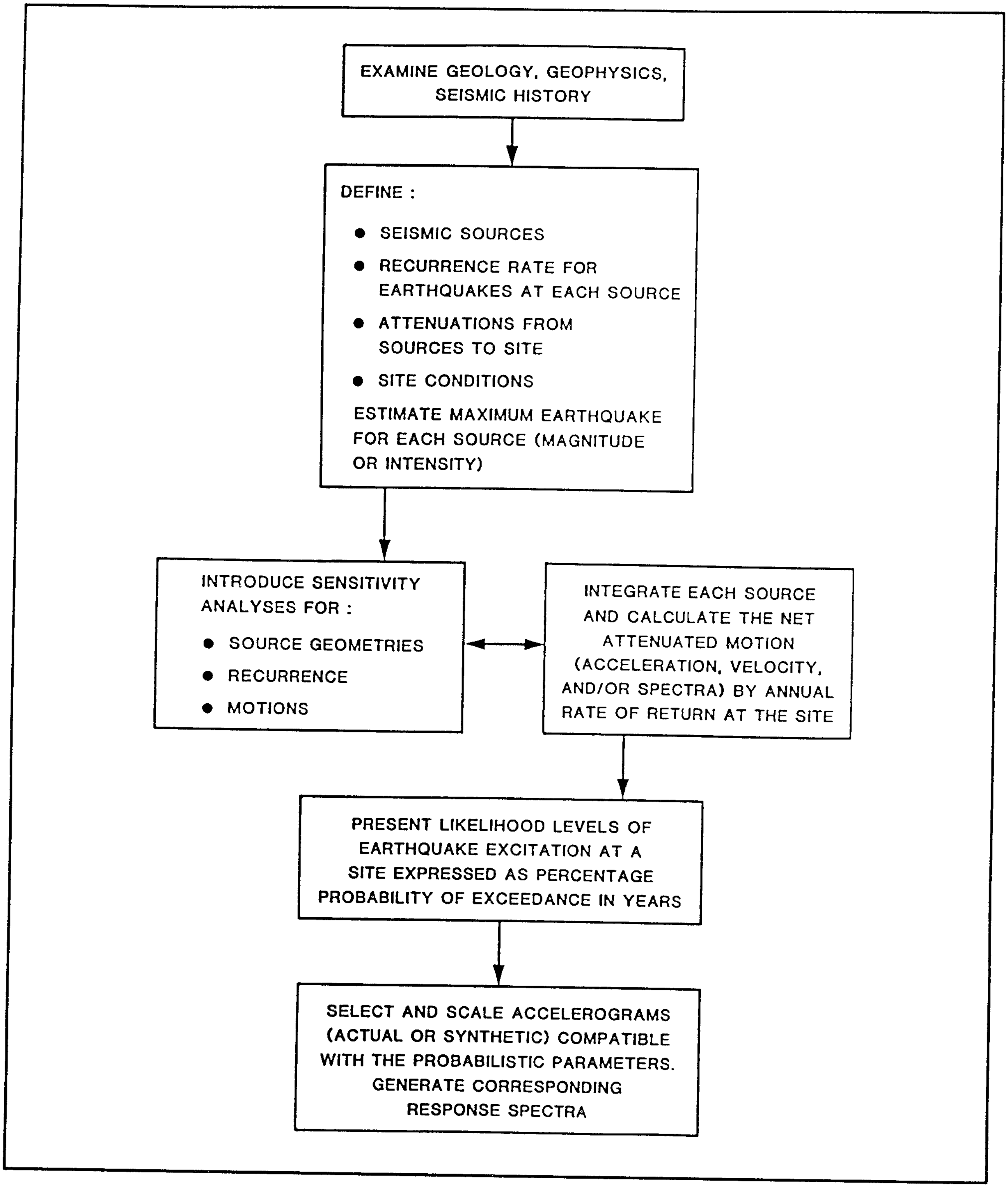


Figure 7-12. Procedure for generating probabilistic earthquake ground motions

can be made for structures in seismically sensitive areas. For structures in areas of low seismic threat, published probability maps are sufficient.

7-8. Direct Assignment of Response Spectra for Earthquake Ground Motions

a. Structural analyses can be performed by beginning with the modal response of a structure and applying suitable spectra as is indicated in Figure 7-13.

(1) Several response spectra from earthquakes of representative sizes and with field conditions appropriate to those of the site can be averaged and smoothed to produce a desired site-specific excitation.

(2) Alternatively, response spectra can be selected that match resonance frequencies found in a structure. The objective is to test the structure in a reasonably conservative manner.

(3) In effect this procedure is a working backward from the behavior of structural components to the input from field conditions. The field conditions should be realistic and they should be selected so as to fully test the structure.

7-9. Other Methods

There are other approaches for describing earthquake ground motions such as:

a. Power spectral densities or root mean square (RMS) accelerations.

b. Equivalent cycles in which accelerograms are altered through calculation against material behavior to provide effective equivalent cycles for testing.

c. Theoretical interpretations that use wave theory to generate synthetic patterns of ground motions.

These and other approaches may prove to be valuable in the future. Today they are mostly still in stages of development.

7-10. Relation of Earthquake Ground Motion to Types of Engineering Analyses

a. The values for motions at any one site obtained by the above procedures are not likely to be the same. However, certain methods were designated as more appropriate than others depending on the region: MM intensity related motions for eastern United States, magnitude and distance motions for western United States when the faults are known, and either of them in preference to probabilistic motions. Additionally, there is a large spread in the motions for all of these categories, requiring that they be represented by mean values and with standard deviations. A question to ask is what level of motion is the most appropriate to use in each of the various categories of engineering analyses that are performed? Tables 7-7 and 7-8 are guides for this purpose of selecting appropriate motions.

(1) Pseudostatic analyses. Earthquake ground motions for various categories of use in pseudostatic analyses are shown in Table 7-7. These are in terms of criticality of structures, seismicity level of the region, and underground cavities. The categories of analyses that are shown are for foundation liquefaction, earth embankments and stability of slopes, earth pressures, and concrete and/or steel frame structures. Whether pseudostatic analyses can be used or not, and levels of earthquake ground motions that are appropriate, are indicated for each of these categories.

(2) Dynamic analyses. Earthquake ground motions for dynamic analyses are shown in Table 7-8. These motions are parameters for the shaping of time histories to provide the cyclic shaking and response spectra for use in dynamic analyses. The motions are also entrance levels into existing response spectra.

b. The OBE allows a large spread of options for both motions and methods of analysis. The indicated parameters are for the shaping of time histories; however, an OBE may be adjusted for economic reasons and its values may be purely an engineering decision. The motion levels in Table 7-8 for the OBE are for conservative evaluations. The OBE may replace an MCE for the design level of a structure when an MCE is not feasible to construct for and there are no hazards to life.

7-11. Summary

The above procedures provide the means for obtaining earthquake ground motions for input to engineering analyses. To keep the work to a minimum, these data should be generated in sequences as follows.

a. Decide whether a site is in a seismically hazardous region or not. Use seismic hazard maps and Table 7-7.

b. Decide whether the structure is critical or noncritical. Determine criticality by using codes, practices, and subjective judgment.

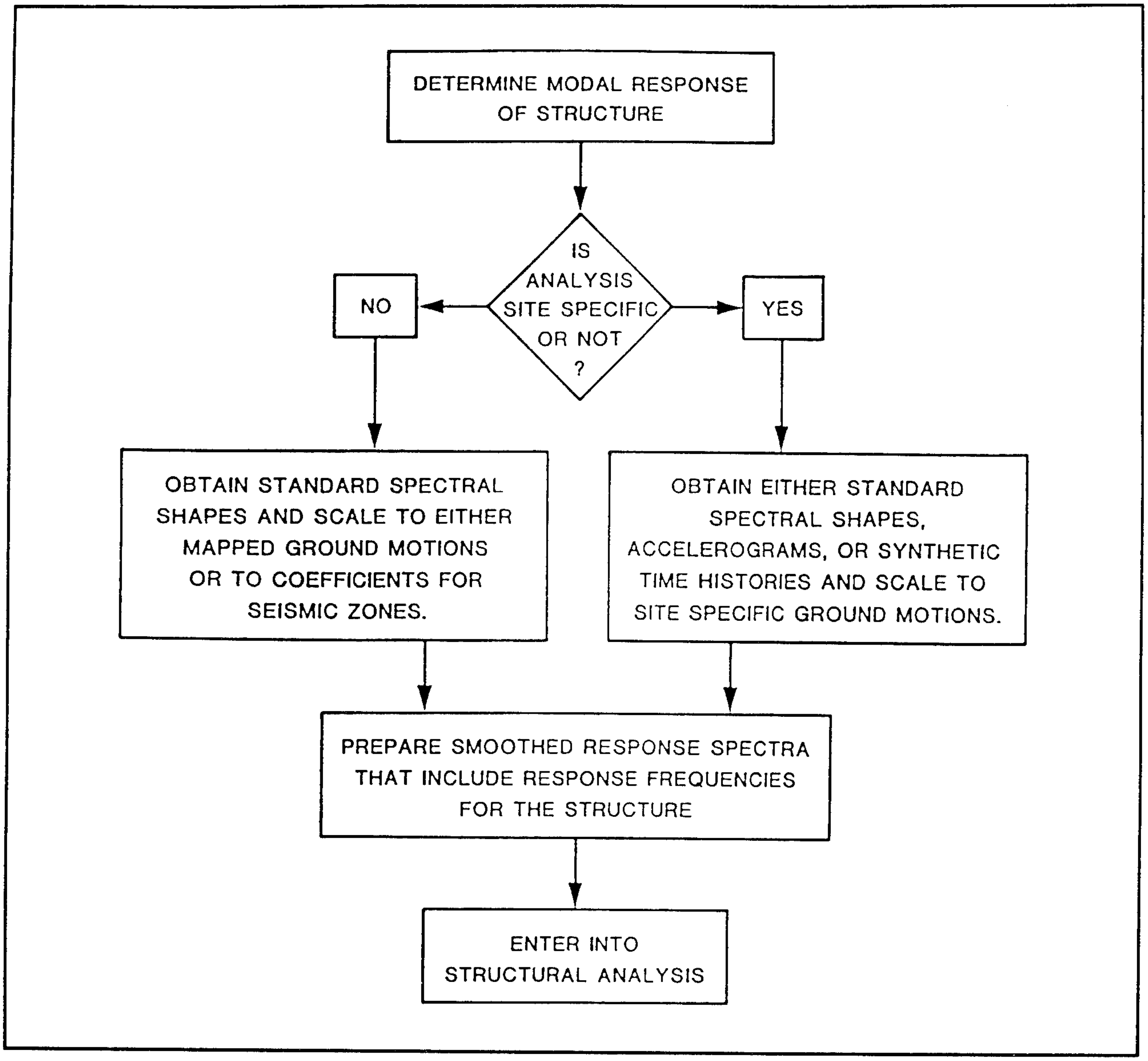


Figure 7-13. Assignment of response spectra for specified earthquake ground motions

Table 7-7
Earthquake Ground Motions for Use in Pseudostatic Analyses. (Adapted from Krinitzsky, Gould, and Edinger 1993)

	Foundation Liquefaction	Earth Embankments and Stability of Slopes	Earth Pressures	Concrete and/or Steel Frame Structures
Noncritical facility in any zone of seismic activity. *Critical facility* in an area of low seismicity.	Pseudostatic analyses do not apply. Use dynamic analyses.	1. Use 1/2 $(A_{max})_{BASE}$ at base for sliding block. 2. A_{max} is obtained from peak horizontal motion (mean)* from: (a) MM intensity (b) Magnitude-distance attenuation (c) Probability ~50 to 250-yr, 90 percent nonexceedance.	1. Peak horizontal motions (mean)* from: (a) MM intensity (b) Magnitude-distance attenuation (c) Probability ~50 to 250-yr, 90 percent nonexceedance. 2. Use 1/2 $(A_{max})_{BASE}$ for backfill.	1. Seismic-zone coefficients/ factors in building codes. 2. For generating ratio of A_{max} to A of structure or element, A_{max} is obtained from peak horizontal motions (mean)* from: (a) MM intensity (b) Magnitude-distance attenuation (c) Probability ~50 to 250-yr, 90 percent nonexceedance.
Critical facility in an area of moderate to strong seismicity.	Use dynamic analyses.	1. Use 1/2 $(A_{max})_{BASE}$ for sliding block. 2. A_{max} from peak horizontal motions (mean + SD)* from: (a) MM intensity (b) Magnitude-distance	1. Peak horizontal motions (mean + SD)* from: (a) MM intensity (b) Magnitude-distance attenuation 2. Use 1/2 $(A_{max})_{BASE}$ for backfill.	1. Seismic-zone coefficients/ factors in building codes. 2. A_{max} from peak horizontal motions (mean + SD)* from: (a) MM intensity (b) Magnitude-distance attenuation
Underground cavity	Use dynamic analyses.	1. Attenuate appropriate peak horizontal motions at ground surface to depth of cavity.		

* Adjust if necessary for site condition; shallow plate boundary, deep subduction zone, or intraplate area; near field or far field; effective motions when near an earthquake source.

Note: A_{max} is the peak value in a time history. It may be obtained as a parameter from the indicated curves or from the probabilistic interpretation.

Table 7-8
Earthquake Ground Motions for Use in Dynamic Analyses. (Adapted from Krinitzsky, Gould, and Edinger 1993)

	Foundation Liquefaction	Earth Embankments and Stability of Slopes	Earth Pressures	Concrete and/or Steel Frame Structures
Critical facility in an area of moderate to strong seismicity. Obtain Maximum Credible Earthquake (MCE).	1. Peak horizontal motions (mean + SD)* 2. Generate time histories.	1. Peak horizontal motions (mean + SD)* 2. Generate time histories.	1. Peak horizontal motions (mean + SD)* 2. Generate time histories.	1. Peak horizontal motions (mean + SD)* 2. Generate time histories. 3. Obtain response spectra for above time histories. 4. Alternatively, go directly to response spectra, entering with the above peak motions. 5. Check response at the natural frequency of the structure.
Obtain Operating Basis Earthquake (OBE).	1. Peak horizontal motions (mean + SD)* 2. Peak motions from probability ~50 to 250-yr, 90 percent exceedance + SD 3. Generate time histories.	1. Peak horizontal motions (mean + SD)* 2. Peak motions from probability ~50 to 250-yr, 90 percent exceedance + SD 3. Generate time histories.	1. Peak horizontal motions (mean + SD)* 2. Peak motions from probability ~50 to 250-yr, 90 percent exceedance + SD 3. Generate time histories.	1. Peak horizontal motions (mean + SD)* 2. Peak motions from probability ~50 to 250-yr, 90 percent exceedance + SD 3. Generate time histories and/or obtain response spectra. 4. Check response at the natural frequency of the structure.
Underground cavity	1. Attenuate appropriate peak horizontal motions at ground surface to depth of cavity. Underground accelerogram records may provide guidance for subsurface spectral content.			

* Obtain peak horizontal motions from (a) MM intensity or (b) magnitude-distance attenuation charts. Adjust for site condition; shallow plate boundary, deep subduction zone, or intraplate area; near field or far field; effective motions when near an earthquake source. Adjust as needed for Operating Basis.

c. For a noncritical structure, in a seismically non-hazardous area, use appropriate building codes and Figure 7-2.

d. For a critical structure, in an area of low seismic threat, use appropriate building codes and Figure 7-2.

e. For a critical structure in a seismically active area, locate the sources of earthquakes that will affect the site. Assign maximum earthquake magnitudes. Follow Figures 7-2 and 7-3. Determine

(1) Is there active fault movement at the site?

(2) Is there a landslide hazard?

(3) Is the foundation or the structure susceptible to liquefaction?

(4) Are there special considerations determinable from dynamic analyses?

f. Assign parameters for site-specific earthquake ground motions.

(1) Intensity-based motions (Figure 7-6 and Appendix B) principally for applications involving seismic zones.

(2) Magnitude-based motions (Figure 7-7 and Appendix C) principally for use with fault sources. Figures 7-2 to 7-8, 7-13, Tables 7-7 and 7-8.

g. Probability values, Figure 7-12, can be obtained from probability maps or procedures in Appendix D. These values can be used for comparative-risk assessments and OBEs.

h. Select accelerograms and/or response spectra appropriate for the above parameters for site-specific earthquake ground motions. Follow Figure 7-13 and Table 7-8.

i. Obtain peer reviews for the field and office studies. Review all possible viewpoints and select among them critically to generate a single viewpoint that has a best informed, most logical, and most defensible set of conclusions.

Appendix A
References

A-1. Required Publications

ER 1110-2-1806
Earthquake Design and Analysis for Corps of Engineers Projects

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A-2. Related Publications

Note: References used in this EM are available on interlibrary loan from the Research Library, ATTN: CEWES-IM-MI-R, U.S. Army Engineer Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

Anagnos and Kiremidjian 1988
Anagnos, T., and Kiremidjian, A. S. 1988. "A review of earthquake occurrence models for seismic hazard analysis," *J. of Prob. Eng. Mech.* 3, 3-11.

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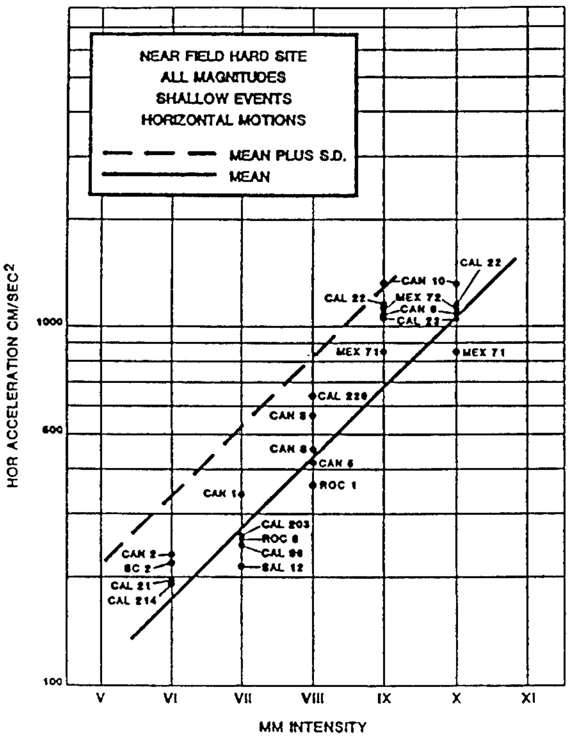
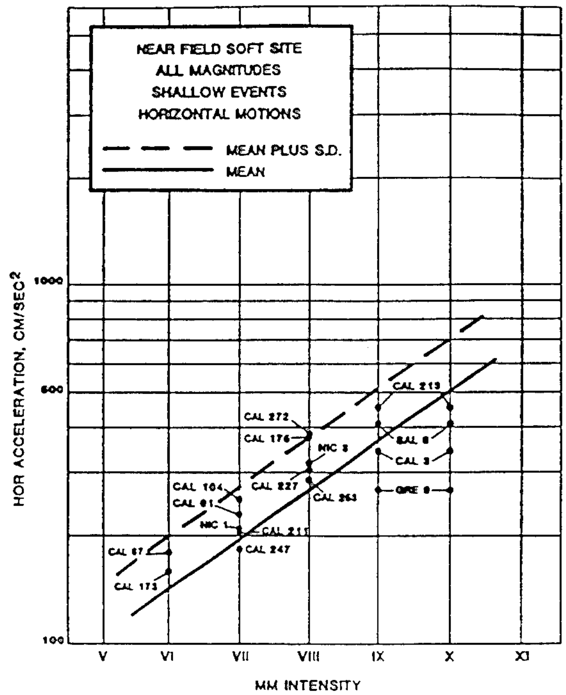
Appendix B
Numeration of Krinitzsky-Chang Curves for Modified Mercalli Intensities and Earthquake Ground Motions with Recommended Accelerograms

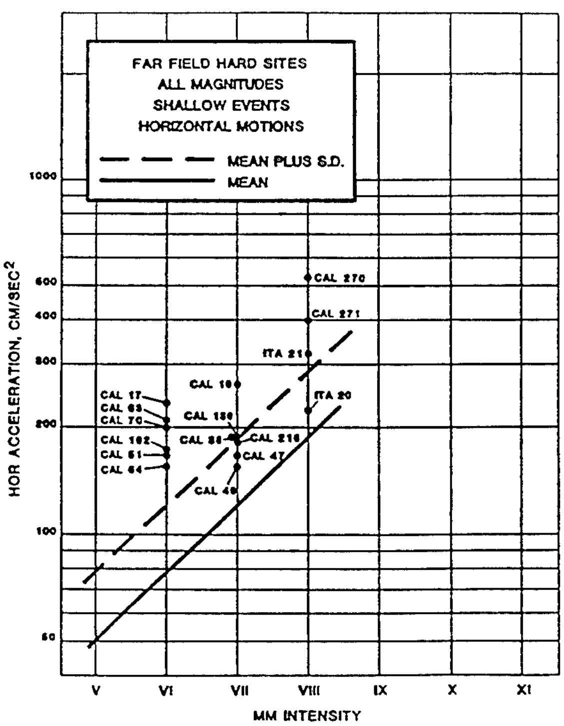
		Near Field		Far Field	
		All Magnitudes		All Magnitudes	
		Hard Site	Soft Site	Hard Site	Soft Site
Brittle Zone Focal Depth ≤ 19 km (Shallow Events)	Acceleration cm/sec^2	B-1	B-2	B-3	B-4
				All Magnitudes Hard Site	All Magnitudes Soft Site
	Velocity cm/sec	B-5	B-6	B-7	B-8
				M ≤ 6.9 Hard Site	M ≤ 6.9 Soft Site
	Duration Bracketed >0.05g, sec	B-9	B-10	B-11	C-12
				All Magnitudes Hard Site	All Magnitudes Soft Site
Subduction Zone Focal Depth ≥ 20 km (Deep Events)	Acceleration cm/sec^2			B-13	B-14
	Velocity cm/sec			B-15	B-16
				M ≤ 6.9 Hard Site	M ≤ 6.9 Soft Site
	Duration Bracketed ≥0.05g, sec			--	B-17
				M = 7.0 - 7.5 Hard Site	M = 7.0 - 7.5 Soft Site
				B-18	B-19
				M ≥ 7.6 Hard Site	M ≥ 7.6 Soft Site
				B-20	B-21


NEAR FIELD HARD SITE
ALL MAGNITUDES
SHALLOW EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR ACCELERATION CM/SEC2
MM INTENSITY

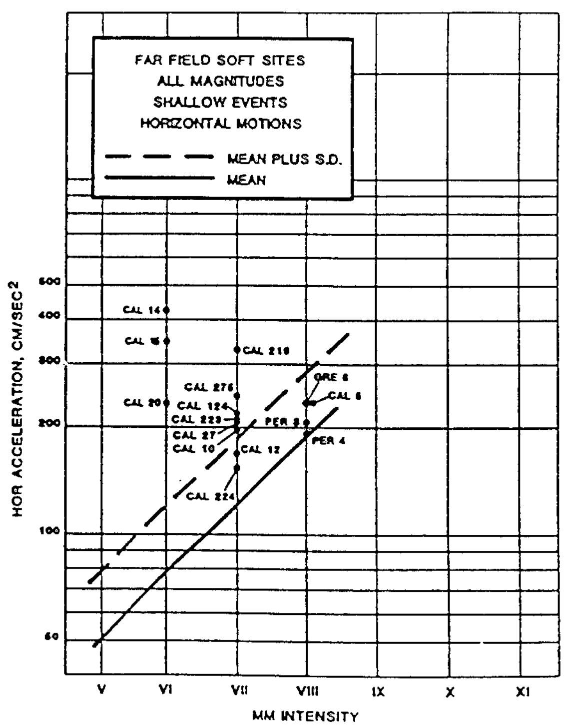
B-1


NEAR FIELD SOFT SITE
ALL MAGNITUDES
SHALLOW EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR ACCELERATION, CM/SEC2
MM INTENSITY

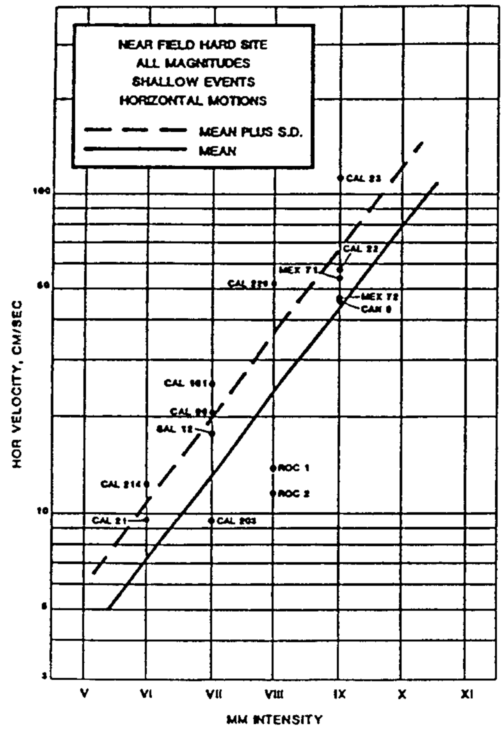
B-2


FAR FIELD HARD SITES
ALL MAGNITUDES
SHALLOW EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR ACCELERATION, CM/SEC2
MM INTENSITY

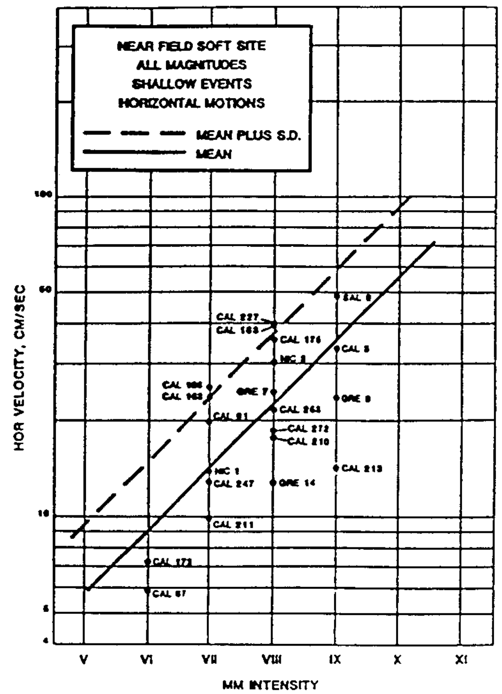
B-3


FAR FIELD SOFT SITES
ALL MAGNITUDES
SHALLOW EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR ACCELERATION, CM/SEC2
MM INTENSITY

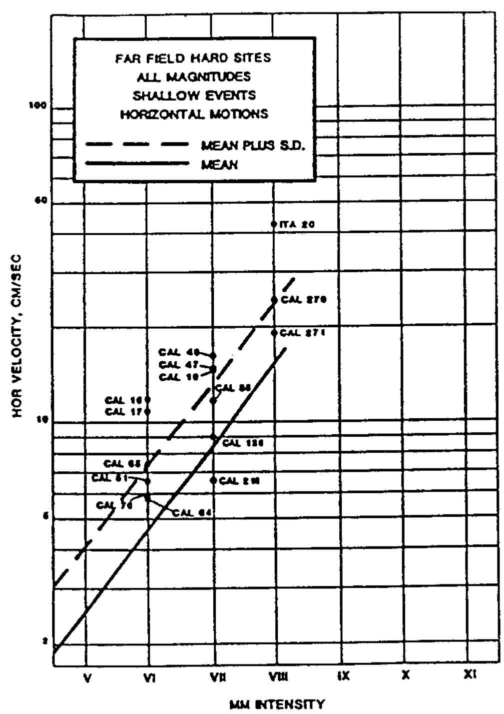
B-4


NEAR FIELD HARD SITE
ALL MAGNITUDES
SHALLOW EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR VELOCITY, CM/SEC
MM INTENSITY
V
VI
VII
VIII
IX
X
XI

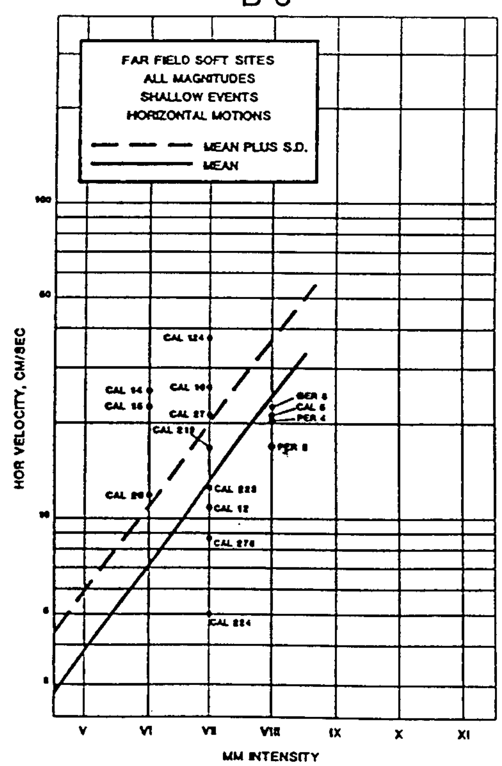
B-5


NEAR FIELD SOFT SITE
ALL MAGNITUDES
SHALLOW EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR VELOCITY, CM/SEC
MM INTENSITY
V
VI
VII
VIII
IX
X
XI

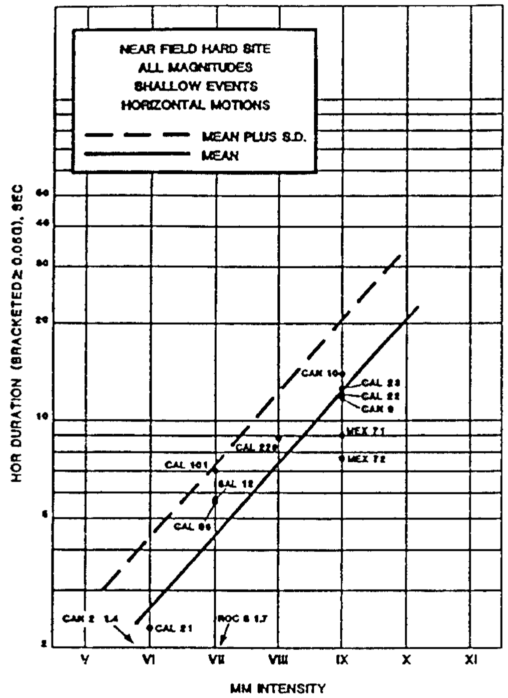
B-6


FAR FIELD HARD SITES
ALL MAGNITUDES
SHALLOW EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR VELOCITY, CM/SEC
MM INTENSITY
V
VI
VII
VIII
IX
X
XI

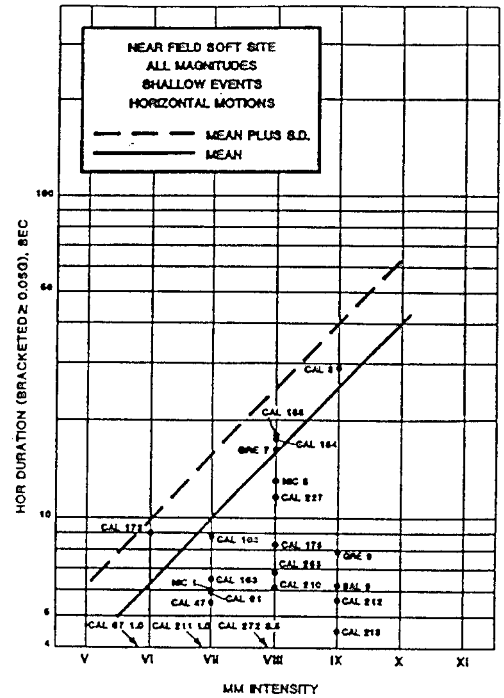
B-7


FAR FIELD SOFT SITES
ALL MAGNITUDES
SHALLOW EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR VELOCITY, CM/SEC
MM INTENSITY
V
VI
VII
VIII
IX
X
XI

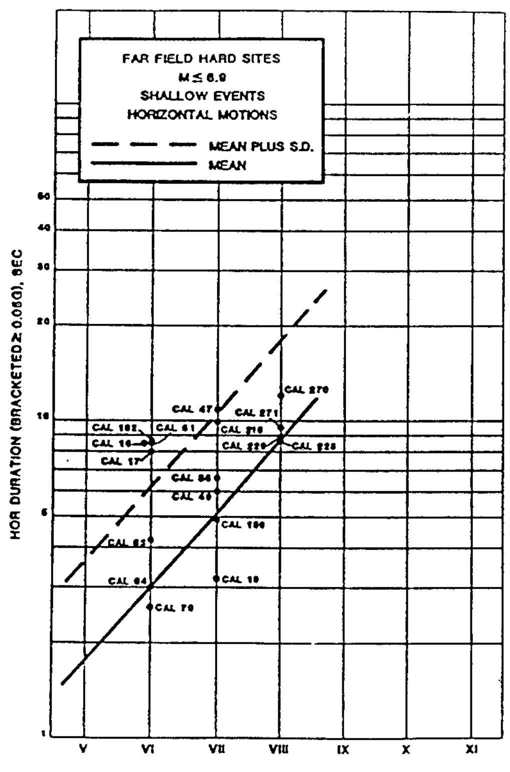
B-8



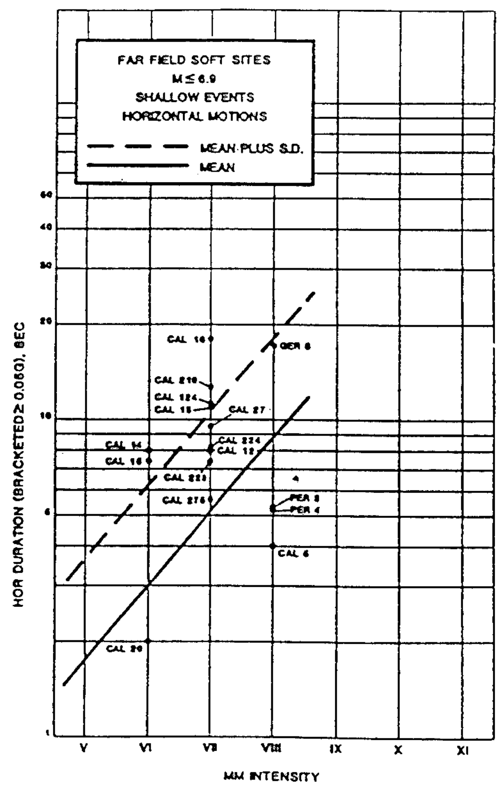
B-9



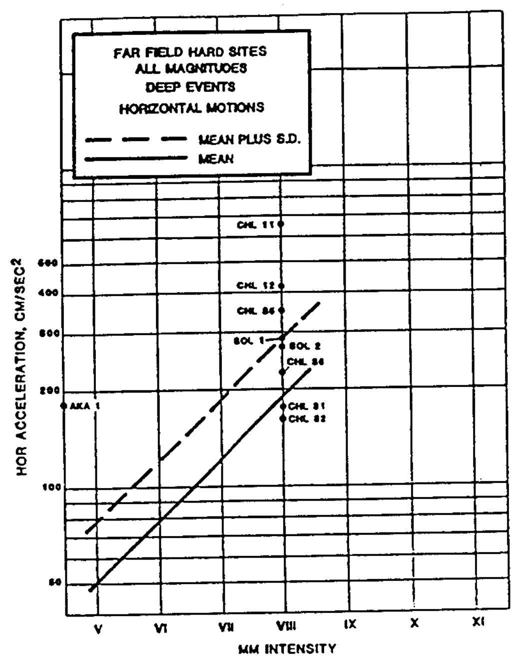
B-10



B-11



B-12



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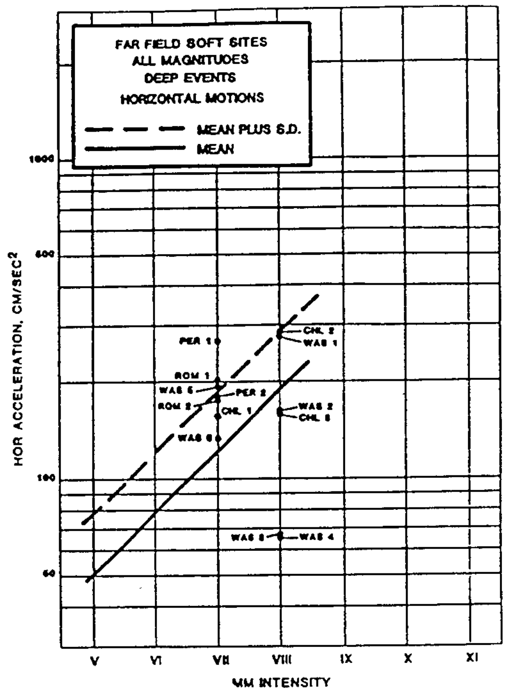
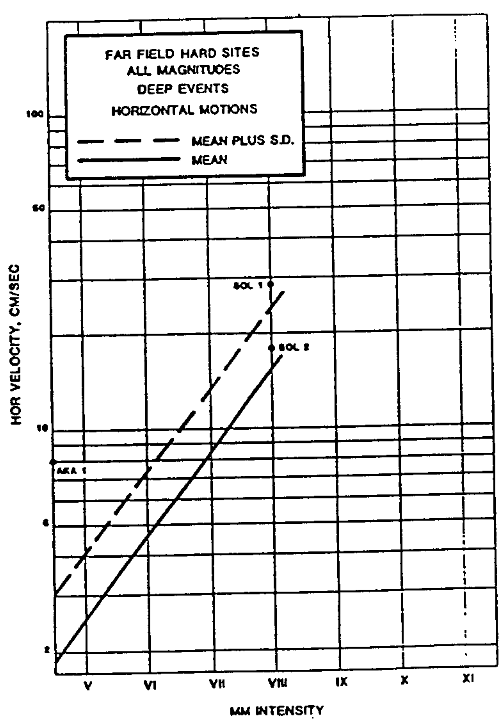
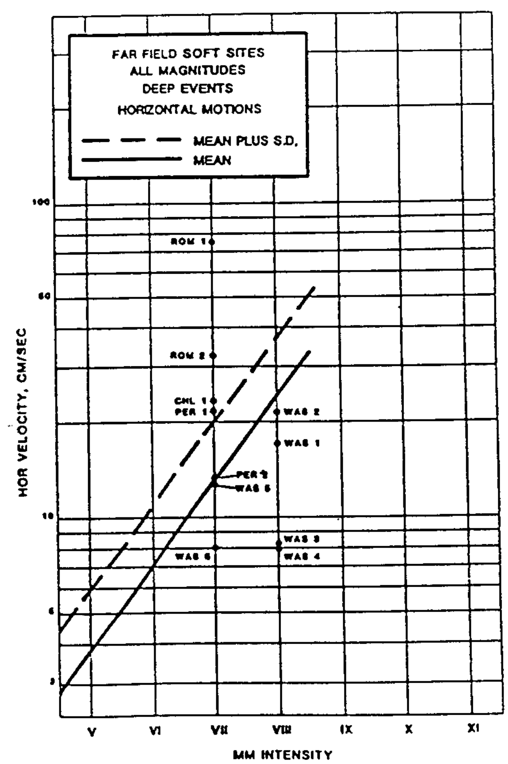


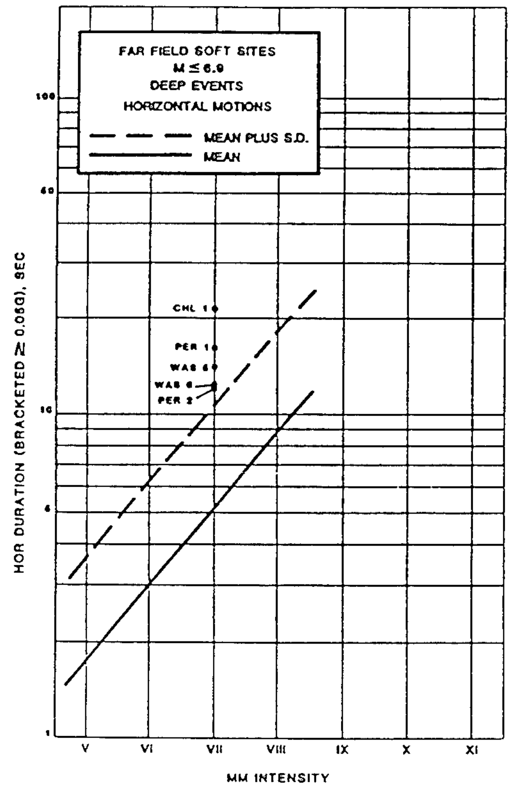
B-14



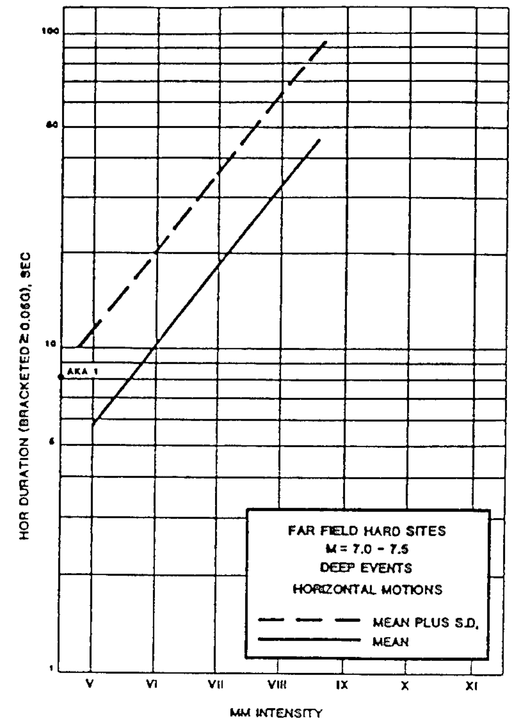
B-15



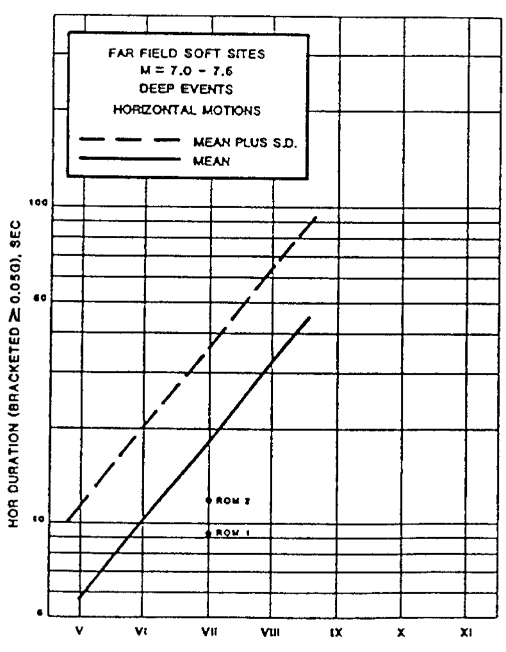
B-16



B-17



B-18



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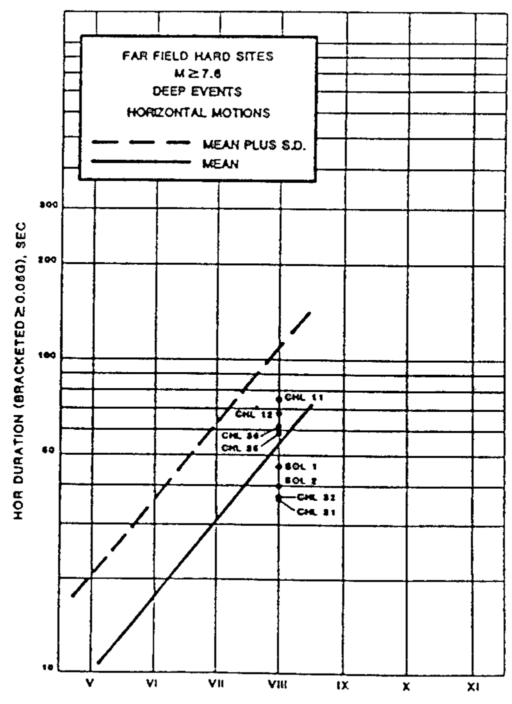

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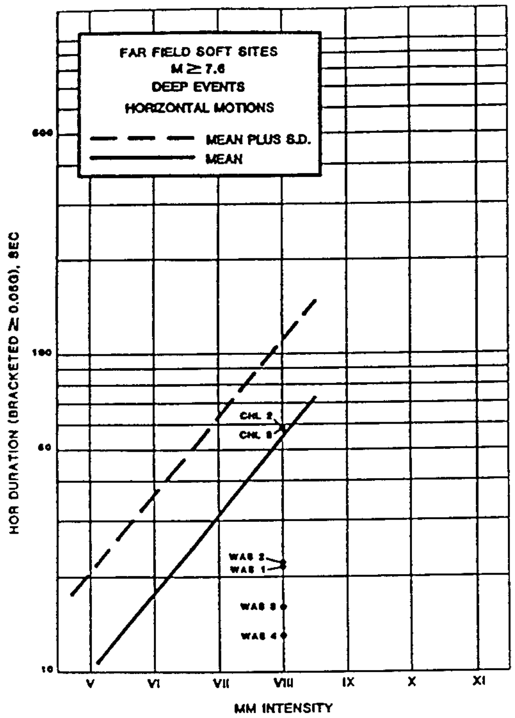
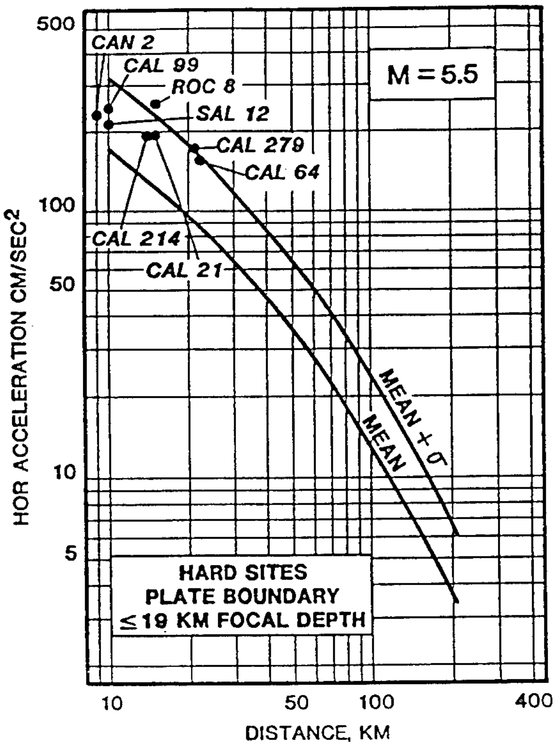

FAR FIELD SOFT SITES
M ≥ 7.6
DEEP EVENTS
HORIZONTAL MOTIONS
MEAN PLUS S.D.
MEAN
HOR DURATION (BRACKETED ≥ 0.05G), SEC
100
50
10
CHL 2
CHL 3
WAS 2
WAS 1
WAS 3
WAS 4
V
VI
VII
VIII
IX
X
XI
MM INTENSITY

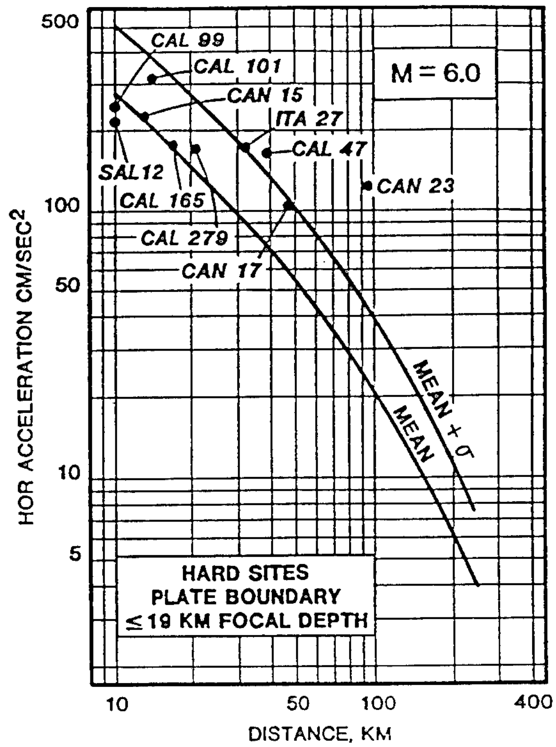
B-21

Appendix C
Numeration of Krinitzsky-Chang-Nuttli Curves for Magnitude, Distance, and Earthquake Ground Motions for Plate Boundaries with Recommended Accelerograms

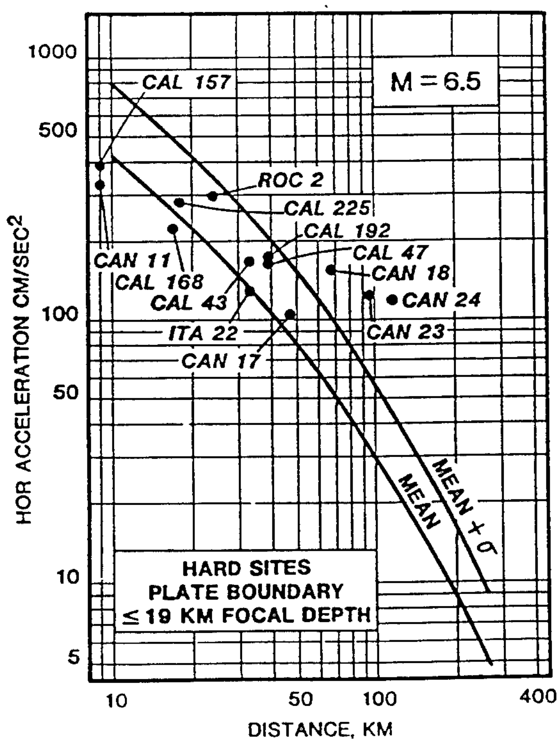
		Focal Depth ≤ 19 km			Subduction Zone Focal Depth ≥ 20 km	
		Hor Accel	Hor Vel	Hor Dur	M	Hor Accel
Hard Site	5.5	C-1	C-6	C-11	5.5	C-31
	6.0	C-2	C-7	C-12	6.0	C-32
	6.5	C-3	C-8	C-13	6.5	C-33
	7.0	C-4	C-9	C-14	7.0	C-34
	7.5	C-5	C-10	C-15	7.5	C-35
Soft Site	5.5	C-16	C-21	C-26		
	6.0	C-17	C-22	C-27		
	6.5	C-18	C-23	C-28		
	7.0	C-19	C-24	C-29		
	7.5	C-20	C-25	C-30		


M = 5.5
CAN 2
CAL 99
ROC 8
SAL 12
CAL 279
CAL 64
CAL 214
CAL 21
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
≤ 19 KM FOCAL DEPTH
HOR ACCELERATION CM/SEC²
500
100
50
10
5
10
50
100
400
DISTANCE, KM

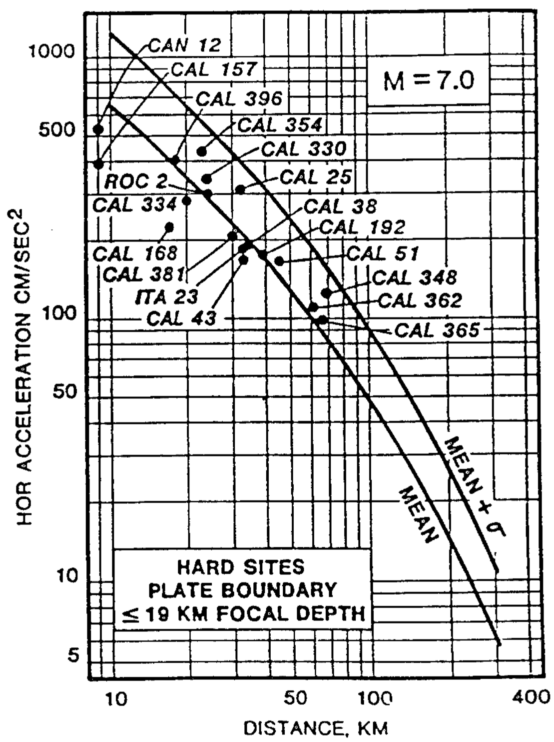
C-1


M = 6.0
CAL 99
CAL 101
CAN 15
ITA 27
CAL 47
CAN 23
SAL12
CAL 165
CAL 279
CAN 17
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
≤ 19 KM FOCAL DEPTH
HOR ACCELERATION CM/SEC²
500
100
50
10
5
10
50
100
400
DISTANCE, KM

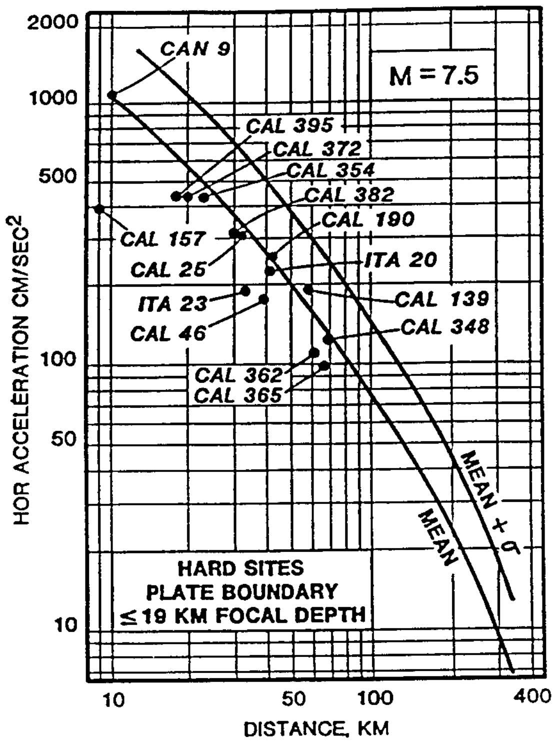
C-2


M = 6.5
CAL 157
ROC 2
CAL 225
CAL 192
CAL 47
CAN 18
CAN 24
CAN 11
CAL 168
CAL 43
ITA 22
CAN 17
CAN 23
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
≤ 19 KM FOCAL DEPTH
HOR ACCELERATION CM/SEC²
1000
500
100
50
10
5
10
50
100
400
DISTANCE, KM

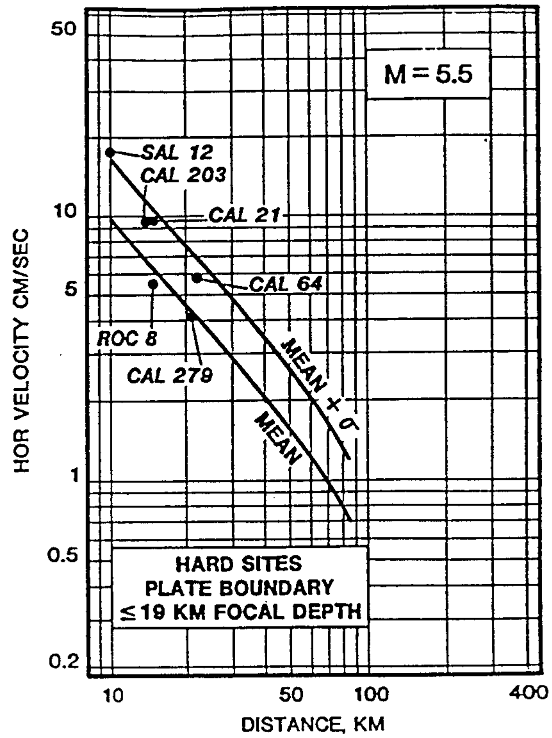
C-3


M = 7.0
CAN 12
CAL 157
CAL 396
CAL 354
CAL 330
ROC 2
CAL 25
CAL 334
CAL 38
CAL 192
CAL 168
CAL 381
CAL 51
CAL 348
ITA 23
CAL 362
CAL 43
CAL 365
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
≤ 19 KM FOCAL DEPTH
HOR ACCELERATION CM/SEC²
1000
500
100
50
10
5
10
50
100
400
DISTANCE, KM

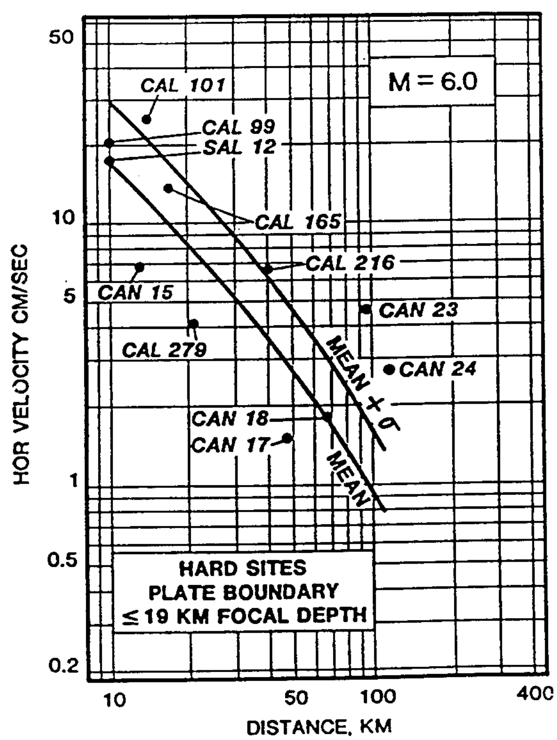
C-4


M = 7.5
HOR ACCELERATION CM/SEC²
DISTANCE, KM
CAN 9
CAL 395
CAL 372
CAL 354
CAL 382
CAL 190
CAL 157
CAL 25
ITA 20
ITA 23
CAL 139
CAL 46
CAL 348
CAL 362
CAL 365
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
≤ 19 KM FOCAL DEPTH

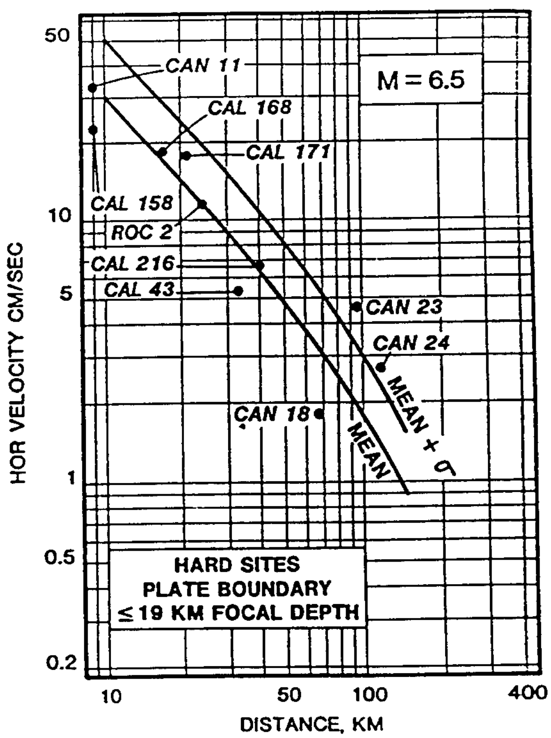
C-5


M = 5.5
HOR VELOCITY CM/SEC
DISTANCE, KM
SAL 12
CAL 203
CAL 21
CAL 64
ROC 8
CAL 279
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
≤ 19 KM FOCAL DEPTH

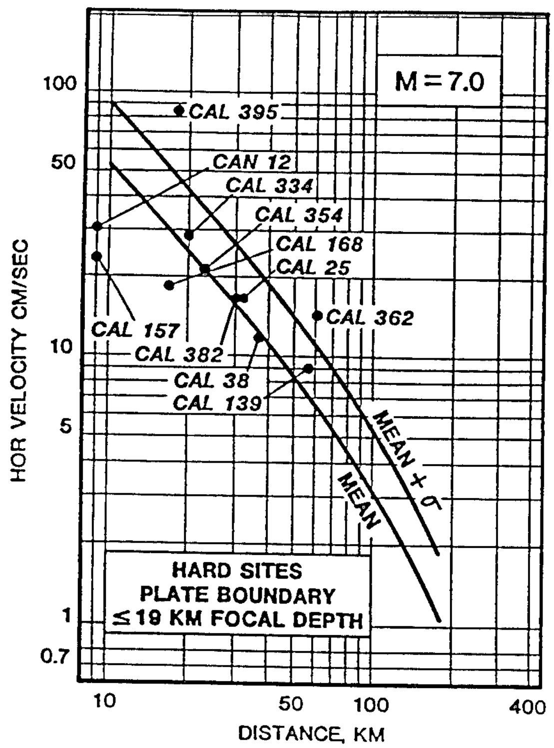
C-6


M = 6.0
HOR VELOCITY CM/SEC
DISTANCE, KM
CAL 101
CAL 99
SAL 12
CAL 165
CAL 216
CAN 15
CAN 23
CAL 279
CAN 24
CAN 18
CAN 17
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
≤ 19 KM FOCAL DEPTH

C-7


M = 6.5
HOR VELOCITY CM/SEC
DISTANCE, KM
CAN 11
CAL 168
CAL 171
CAL 158
ROC 2
CAL 216
CAL 43
CAN 23
CAN 24
CAN 18
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
≤ 19 KM FOCAL DEPTH

C-8



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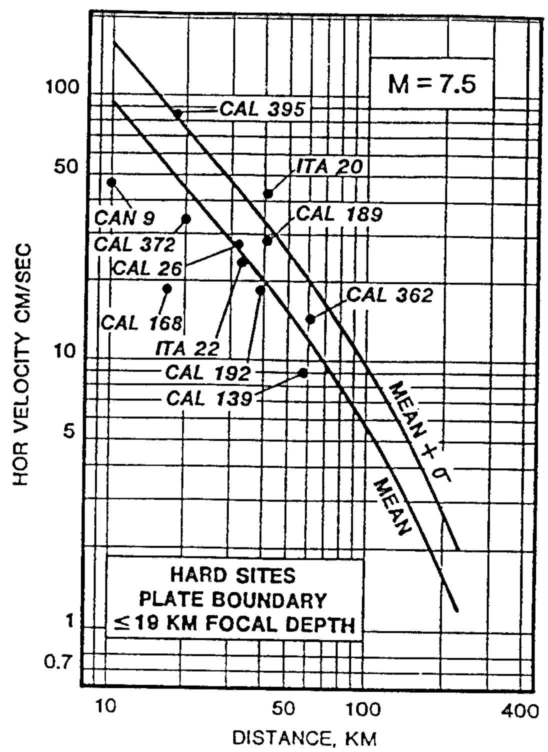

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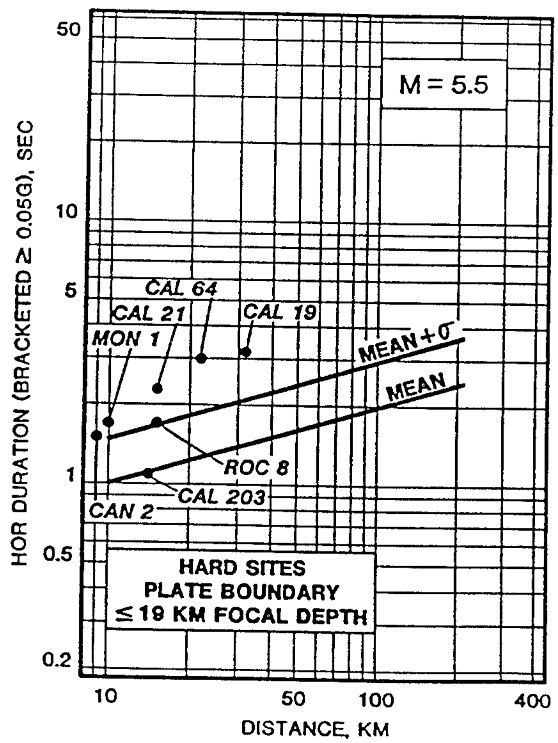

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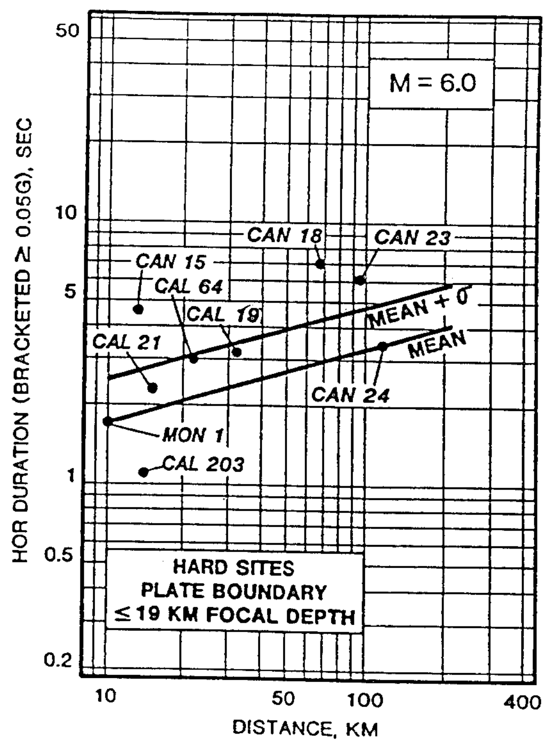

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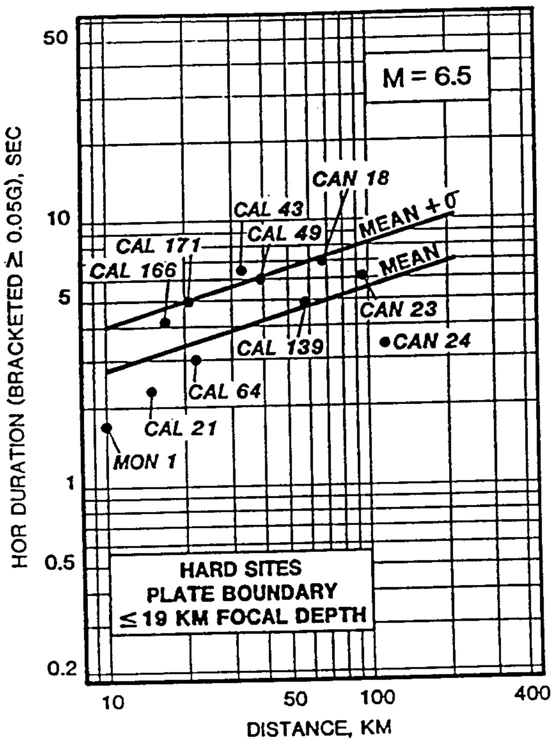

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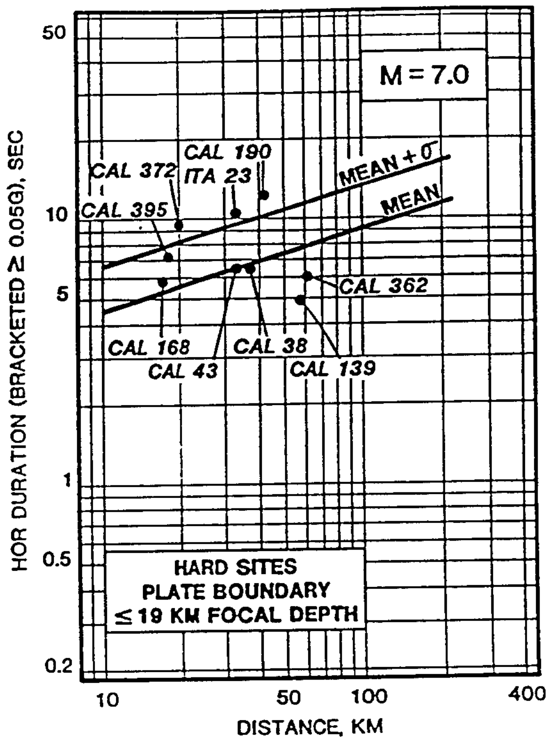

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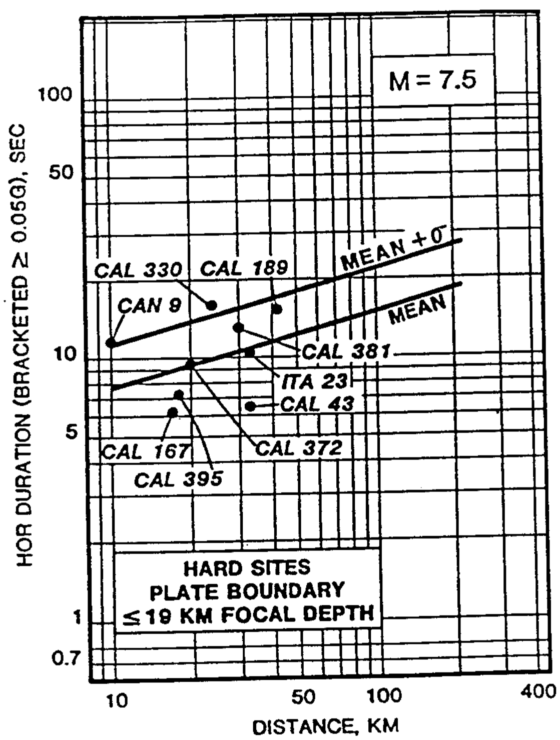

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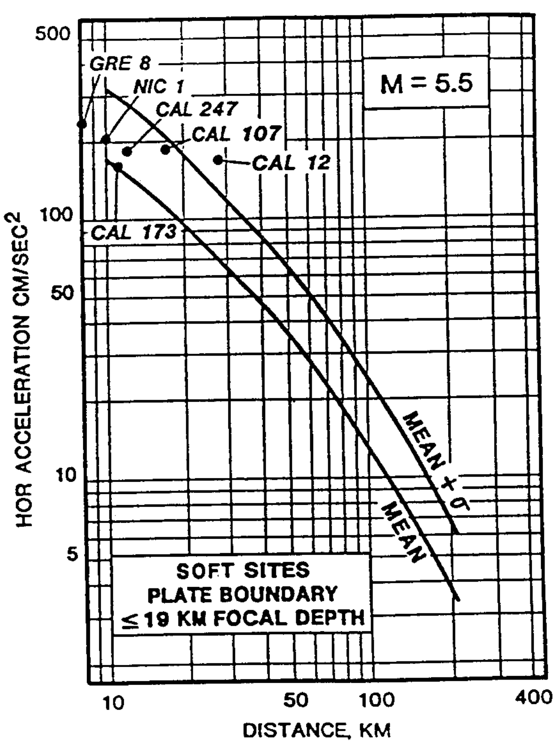

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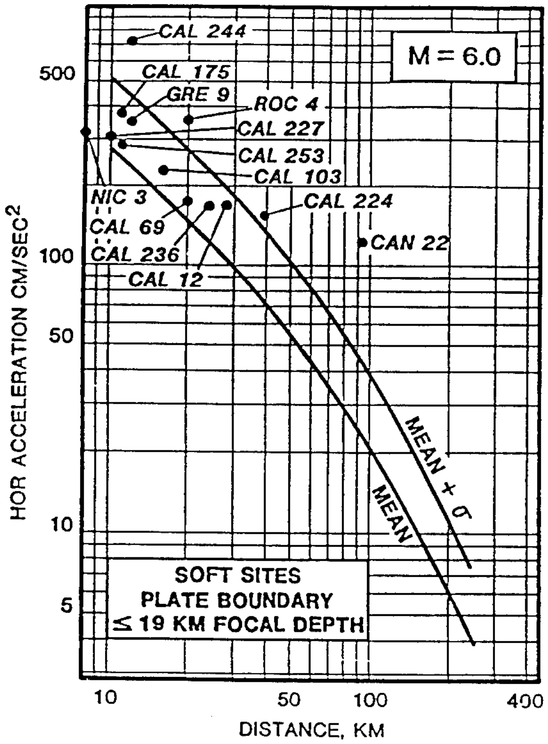

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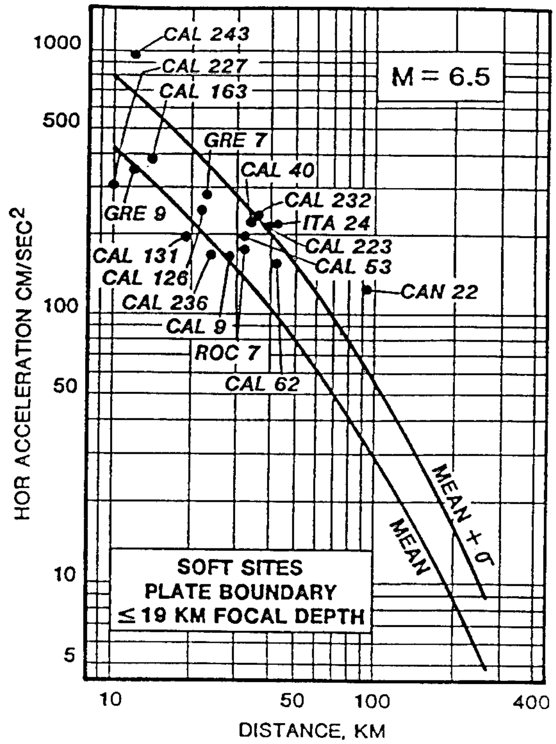

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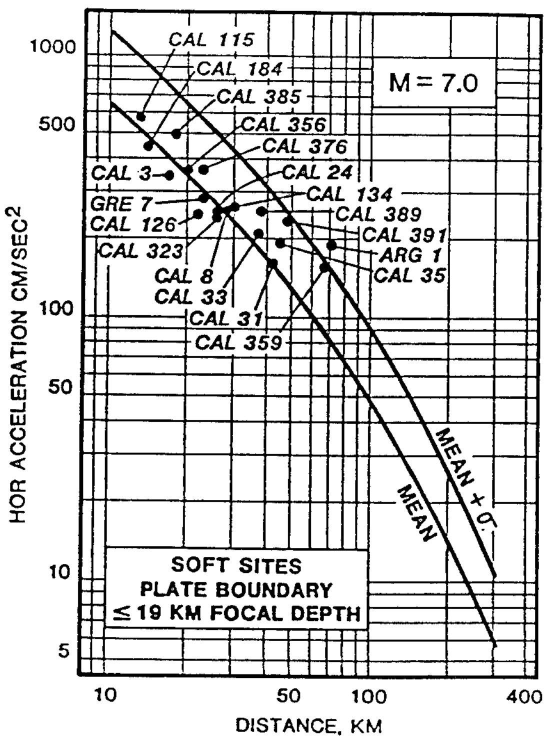

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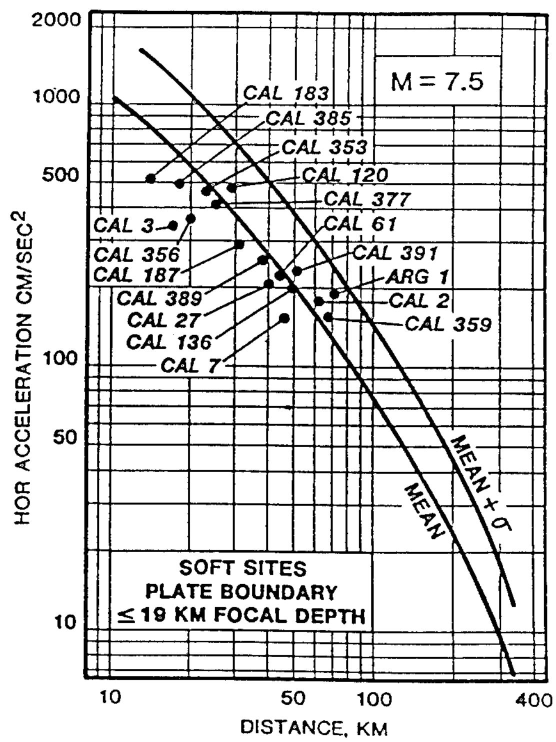

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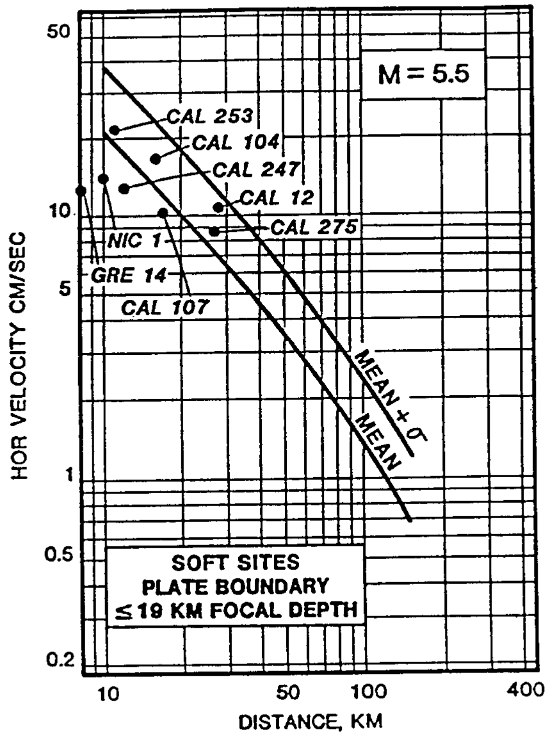

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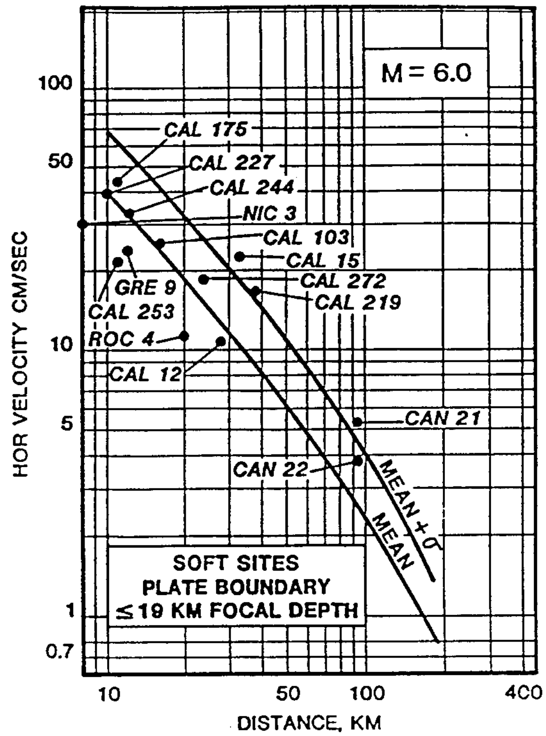

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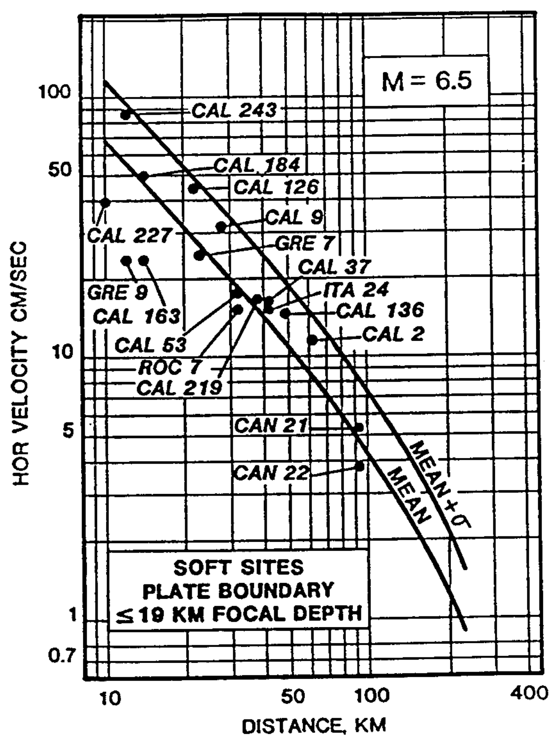

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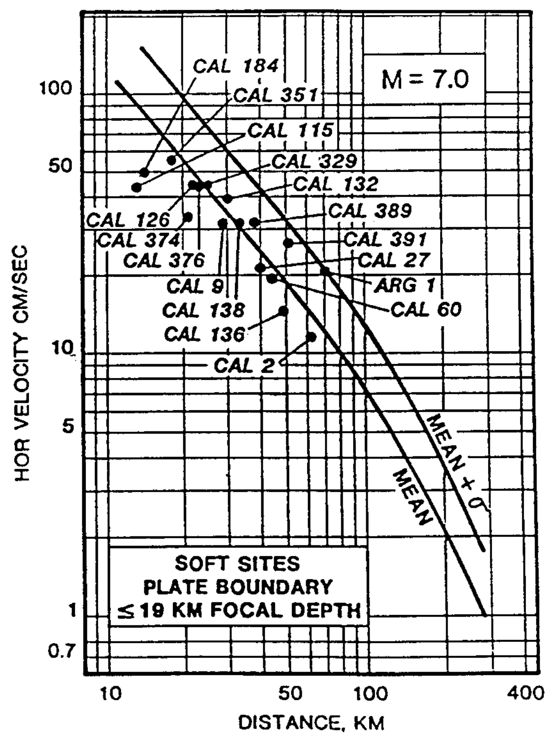

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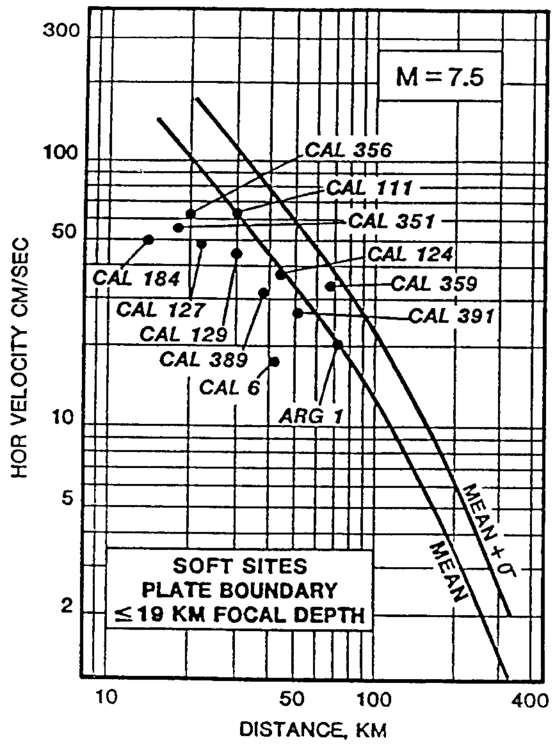

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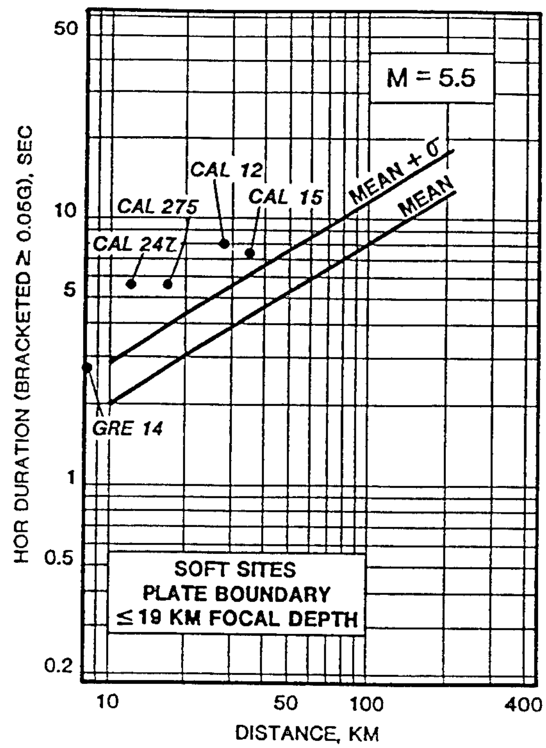

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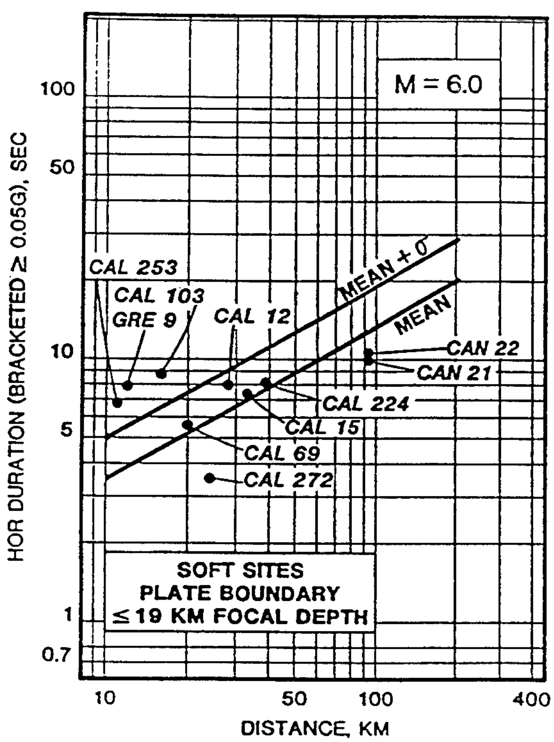

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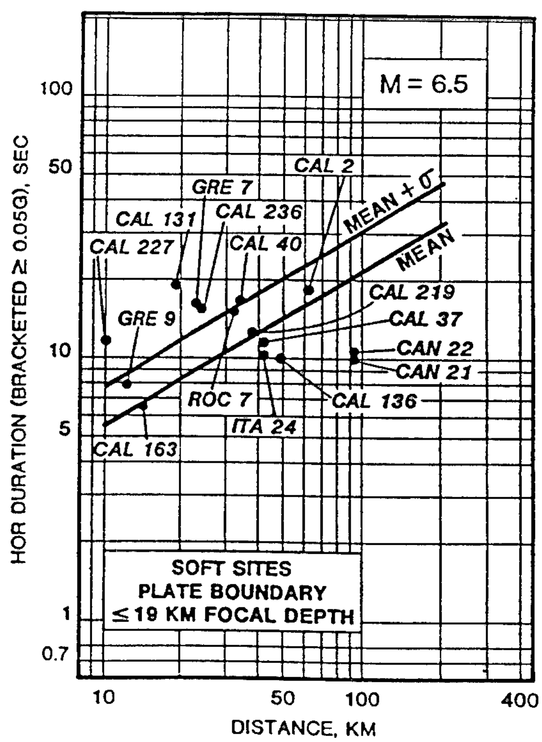

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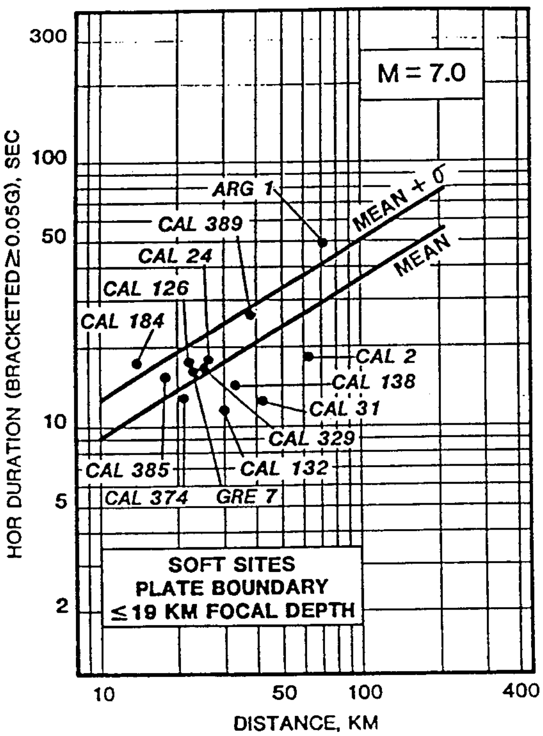

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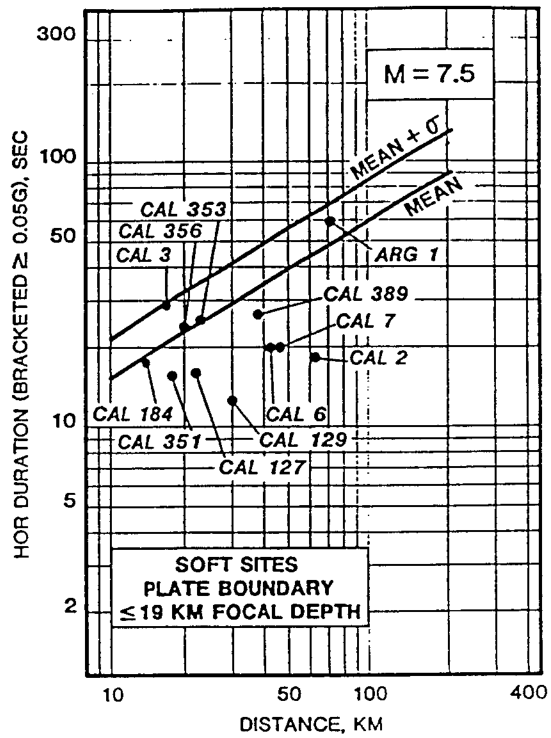

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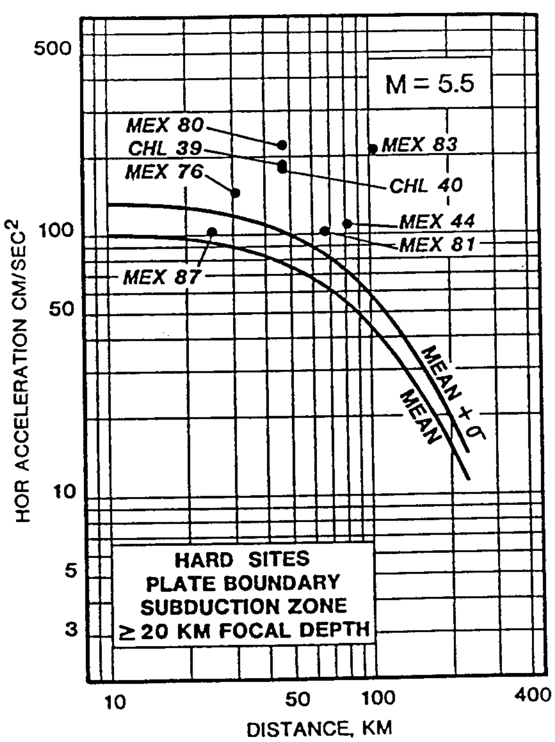

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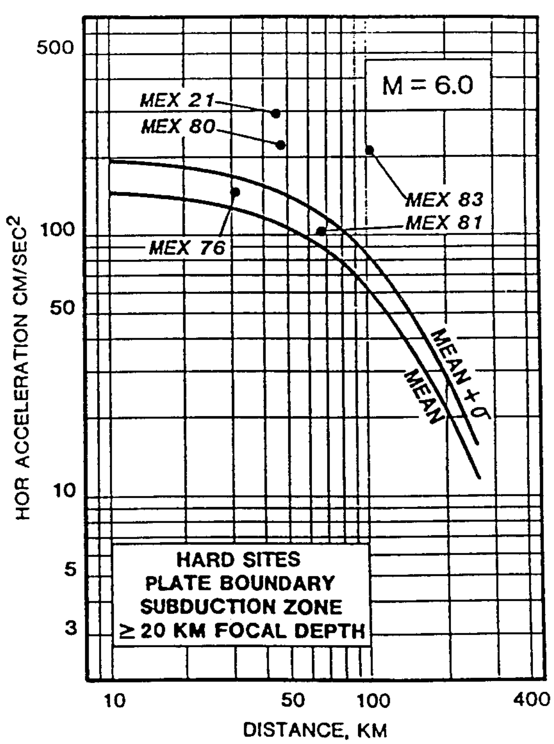

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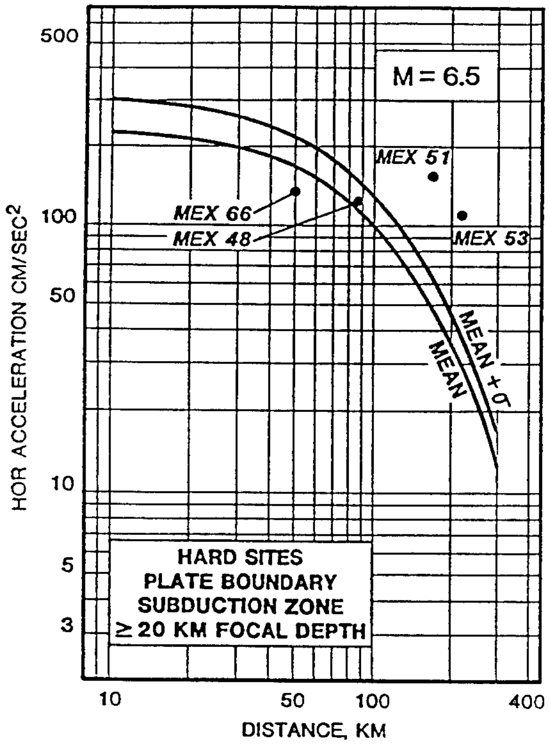
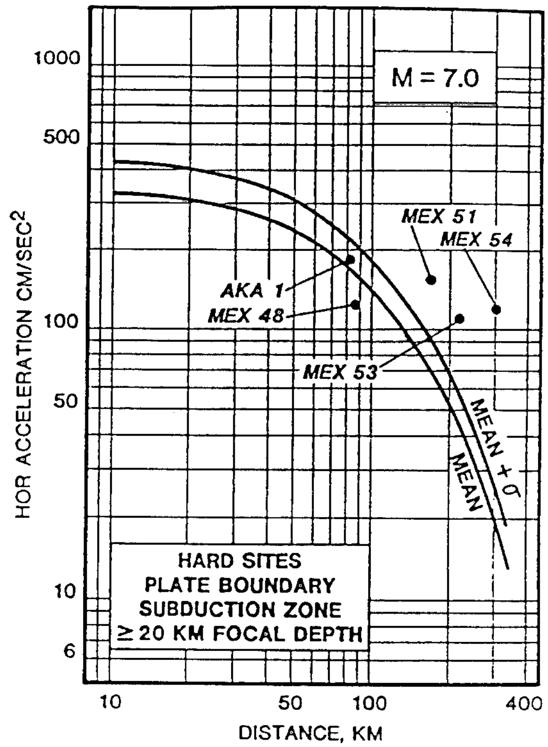

M = 6.5
MEX 51
MEX 66
MEX 48
MEX 53
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
SUBDUCTION ZONE
≥ 20 KM FOCAL DEPTH
HOR ACCELERATION CM/SEC²
DISTANCE, KM

C-33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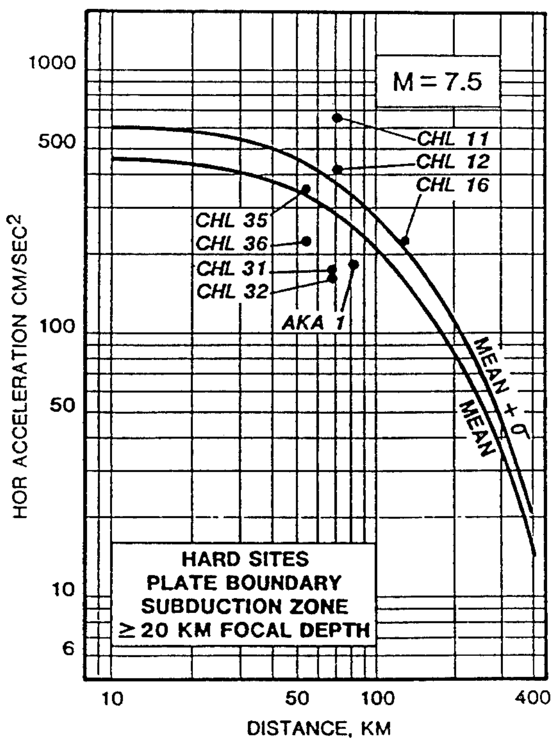
MEX 51
MEX 54
AKA 1
MEX 48
MEX 53
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
SUBDUCTION ZONE
≥ 20 KM FOCAL DEPTH
HOR ACCELERATION CM/SEC²
DISTANCE, KM

C-34


M = 7.5
CHL 11
CHL 12
CHL 16
CHL 35
CHL 36
CHL 31
CHL 32
AKA 1
MEAN + σ
MEAN
HARD SITES
PLATE BOUNDARY
SUBDUCTION ZONE
≥ 20 KM FOCAL DEPTH
HOR ACCELERATION CM/SEC²
DISTANCE, KM

C-35

Appendix D
Probabilistic Seismic Hazard Analyses

D-1. Introduction

a. A probabilistic seismic hazard analysis (PSHA) is a quantitative procedure for incorporating the element of time in the assessment of the earthquake threat at a site. A PSHA attempts to formally account for uncertainties in various geologic and seismologic information and the process of earthquake occurrences in an idealized mathematical model. The objective of a PSHA is to compute for a given exposure time the probability of exceedance corresponding to various levels of a ground motion parameter. Typically the period of interest is one year and the ground motion parameter is either peak horizontal ground acceleration (PGA) or ordinates for pseudovelocity response spectra (S_v).

b. Although several PSHA methods exist, the most frequently used are based on the following three steps (after Cornell 1968):

(1) Establish the location and geometry of all significant potential earthquake sources in the region of the site (typically within a radius of a few hundred kilometers). For each source determine seismicity parameters such as rate of earthquake activity, the probability distribution for earthquake magnitude, and the MCE.

(2) Select an appropriate attenuation relationship to estimate the site ground motion parameter as a function of earthquake magnitude, source to site distance, and various site conditions.

(3) Integrate this information in an earthquake process model to calculate the probability of exceedance in a specified time interval for several values of the site ground motion parameter. For structural analyses, this ground motion parameter is typically used to construct response spectra.

c. These steps are shown in Figure D-1 for PGA and Figure D-2 for S_v. Steps 1 and 2 are provided by a thorough Deterministic Seismic Hazard Assessment (DSHA); probabilistic modeling is introduced in step 3. Consequently, in order to perform a PSHA, a DSHA must be completed first to provide the necessary data. Numerous judgments, assumptions, and approximations are further required to perform PSHA and interpret results due in part to shortcomings in our present understanding of earthquake sources, earthquake occurrence processes, and source-to-site ground motion relationships, as well as inadequacies in our earthquake catalogues.

D-2. Earthquake Source Zones and Seismicity Parameters

a. The locations and geometry of earthquake source zones, MCE values, and background seismicity are identified in the DSHA by detailed geological-seismological investigations. Typically, concentrated sources are represented as points, faults are represented as lines, and areas are represented as polygons for the mathematical model.

b. For each source zone, the frequency of earthquake occurrence is generally estimated from the earthquake catalogue for that zone, augmented by tectonic slip and paleoseismic information if available. Although several earthquake occurrence models exist (see Anagnos and Kiremidjian 1988 for summary) the Gutenberg-Richter (1954) equation is most commonly used (Figure D-3):

$$\log N(m) = a - bm \tag{D-1a}$$

or

$$N(m) = 10^a \exp(-\beta m) \tag{D-1b}$$

where

$N(m)$ = the average number of earthquakes with magnitude greater than or equal to m occurring in a given time period

10^a = the average total number of earthquakes for the time period (also called the activity rate)

b = the relative rate of occurrence of earthquakes with various magnitudes

$\beta = b \ln 10$

Usually, a and b (or β) are assumed to be constant within a source zone. This information is then used to derive a probability density function, $f_m(M)$, for magnitude within the source zone (if there is an earthquake, what is the probability that it will have a certain magnitude?). This density function is typically truncated at a minimum magnitude, M_o, to eliminate magnitudes too small to be of engineering interest, and also at an upper bound magnitude, M_u, which typically corresponds to the MCE. Parameters a and b are typically estimated from the earthquake catalogue.

c. The shortcomings of this simplistic model have been described elsewhere in this manual and by Krinitzsky (1993). For data from a single source zone, a

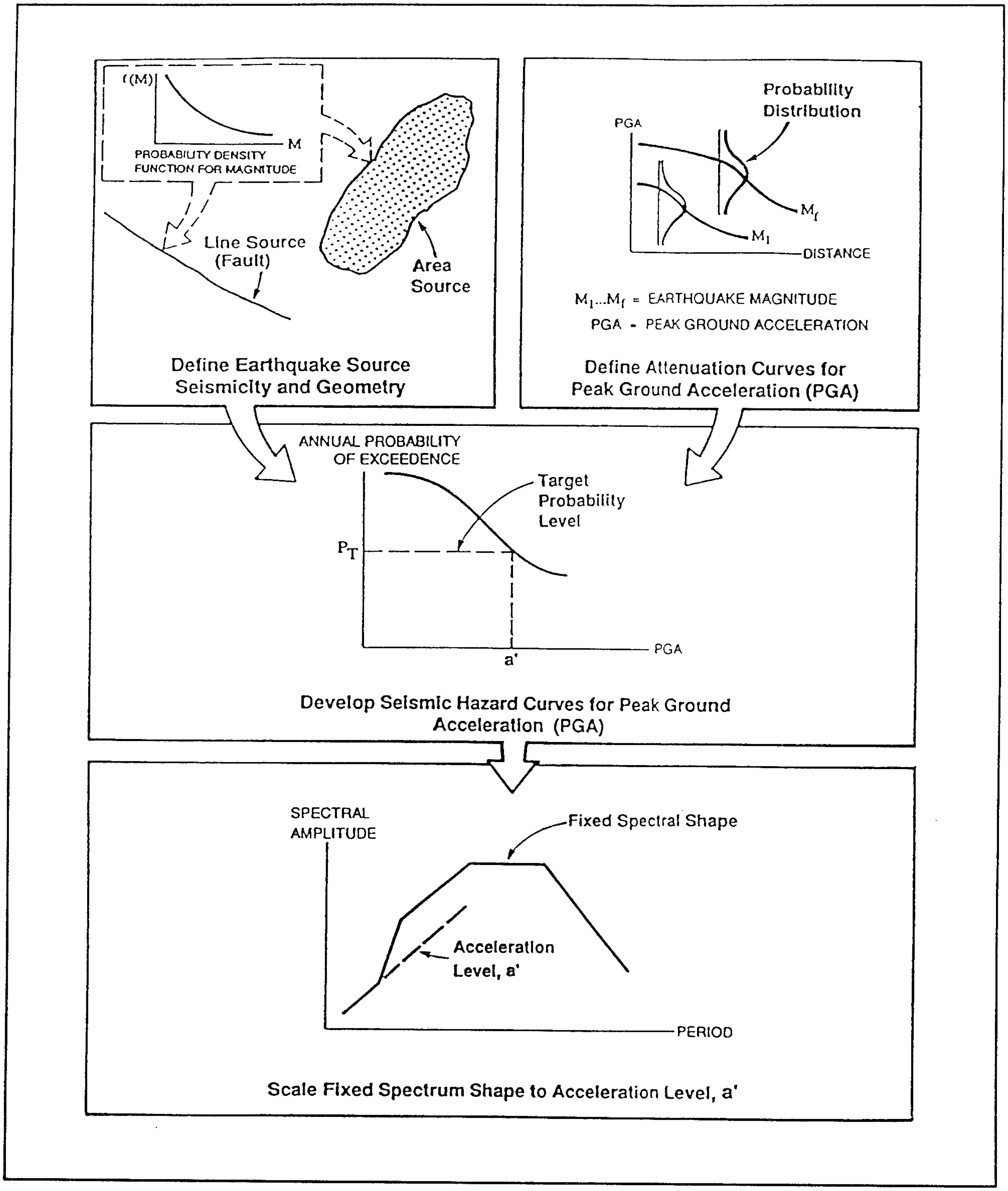


Figure D-1. Steps in a probabilistic seismic hazard analysis for peak ground acceleration (after EERI 1989)

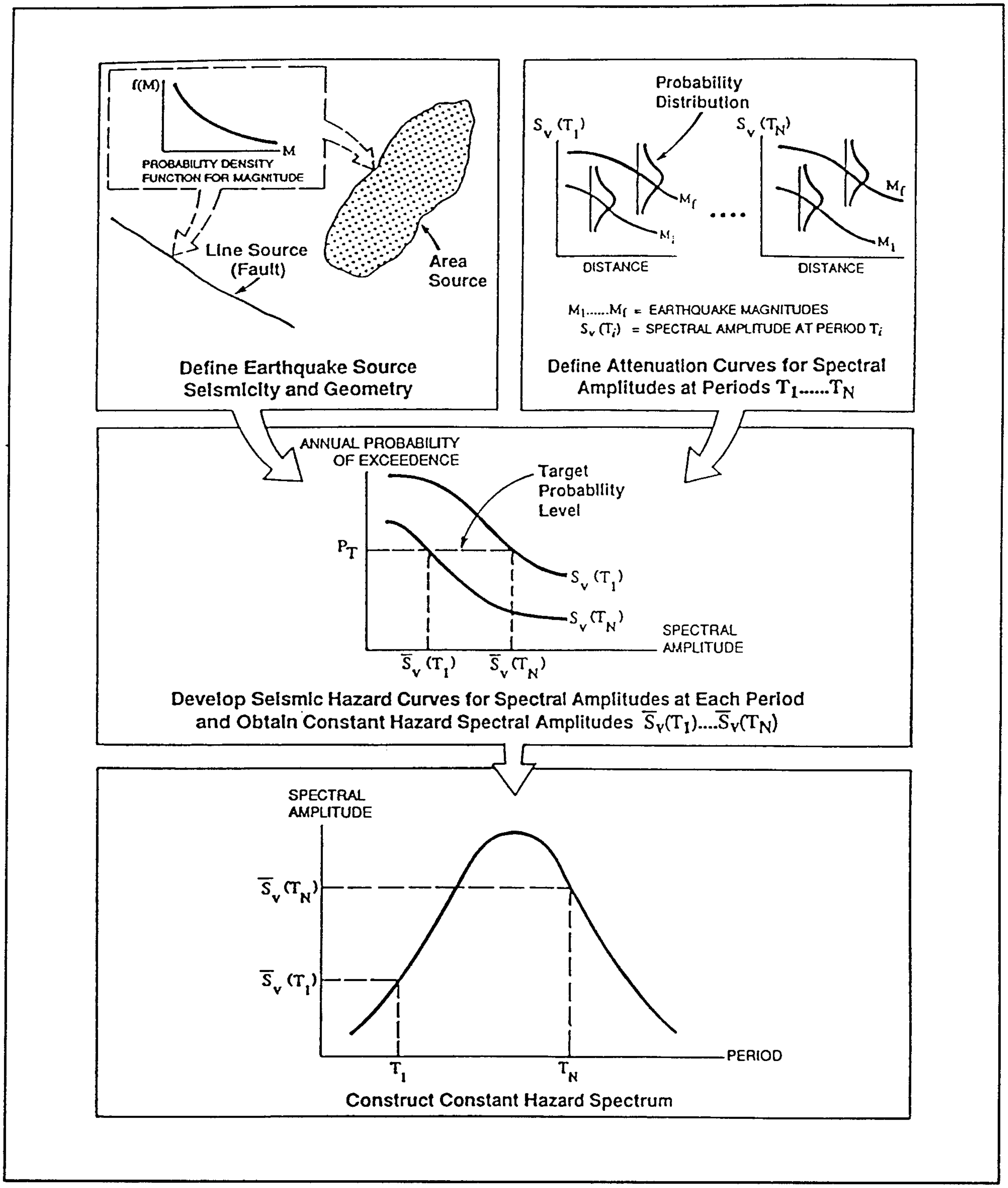
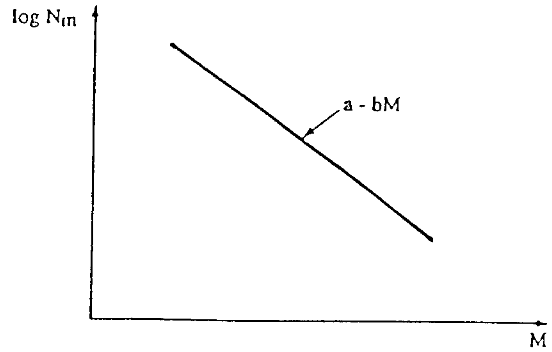


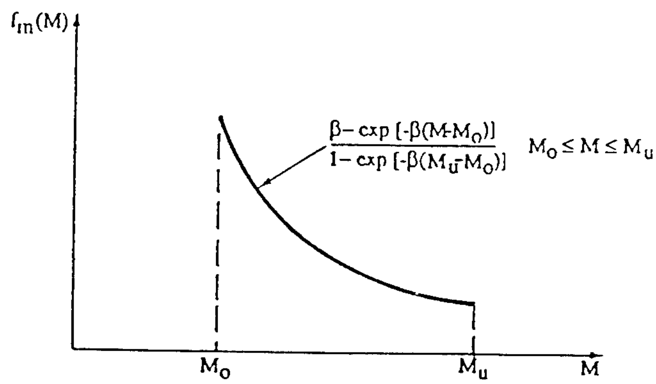
Figure D-2. Steps in a probabilistic seismic hazard analysis for equal hazard response spectra (after EERI 1989)



N_m = Number of Earthquakes with Magnitude $\geq M$ in Given Region and Time

a, b = Regional Seismicity Parameters

(a) Frequency of Earthquake Occurrence



$f_m(M)$ = Probability Density Function of Magnitude M

$\beta = 2.3b$ = Seismicity Parameter

M_o, M_u = Lower Bound and Upper Bound Magnitudes for each Source

(b) Probability Density Function of Magnitude

Figure D-3. Frequency of earthquake occurrence model and probability density function for earthquake magnitude (after EERI 1989)

plot like that shown in Figure D-3 typically will not yield a straight line nor will it be continuous; the occurrence of large earthquakes in particular are generally not consistent with this model. The historical earthquake catalogue is the primary database for estimating the parameters *a* and *b*. The earthquake catalogue in the United States has numerous inadequacies, mainly incompleteness and inaccuracies. Incompleteness results in part from the relatively short period of time that earthquake data have been collected in the United States, only a few hundred years in the eastern United States, and less than that in the western United States. The catalogue contains inaccuracies in part because instrumental data have been collected only for a portion of this century. With the present United States earthquake catalogue and our understanding of earthquake processes, it can be difficult to accurately distinguish between main seismic events and the clusters formed by foreshocks, aftershocks, and related events. Consequently, PSHA typically includes extensive sensitivity analyses of input parameters to provide insight about their impact on computed results.

D-3. Attenuation Relationships

a. In PSHA the equation used to relate a ground motion parameter of interest, *A*, to magnitude, *M*, and source-to-site distance, *R*, generally has the form:

$$\log A = C_1 + C_2 M + C_3 \log (R + C_4) \qquad \text{(D-2)}$$

where C_1, C_2, C_3, and C_4 are empirically derived constants. Additional terms may be added to account for local site effects or uncertainty in Equation D-2. Numerous attenuation relationships have been developed to estimate peak ground motions such as acceleration and velocity (see Appendixes B and C, or McGuire 1976 or Campbell 1985 for summaries), and Arias intensity (Campbell and Duke 1974a, b). A number of attenuation equations are provided with the program documentation for WESRISK (Sykora and Wallace 1993).

b. Joyner and Boore (1988) have developed a family of attenuation relationships for pseudovelocity spectral ordinates used to compute equal-hazard response spectra. These equations have the form:

$$\log_{10}(S_v) = a + b\,(M-6) + c\,(M-6)^2 + d \log_{10}(r) + k\,r + s \qquad \text{(D-3)}$$

where

S_v = spectral velocity for the period defined by the empirical constants (cm/sec)

M = moment magnitude ($5.0 \le M \le 7.7$)

$r = (r_o^2 + h^2)^{1/2}$

r_o = shortest distance (km) from recording site to vertical projection of earthquake fault rupture on surface

a, b, c, h, d, k, s are empirical constants which depend upon the period of the spectral value.

The Joyner and Boore (1988) equation is empirical and was developed based on data from the larger of the two horizontal components of pseudovelocity response at recording stations. The predictive equation is applicable for 5 percent damping only, and represents stiff site conditions. Table D-1 lists the period-dependent empirical constants to be used in the predictive equation for S_v attenuation and period-dependent standard deviations. To account for other soil conditions, the site factor *s* in Equation D-3 can be modified:

$$s = e \log_{10} (V_s/V_{so}) \qquad \text{(D-4)}$$

where V_s is the estimated site shear wave velocity (in m/sec) averaged to a depth of one-quarter wavelength at the period of interest, and *e* and V_{so} are given in Table D-1 (Joyner and Fumal 1984).

D-4. Probabilistic Seismic Hazard Calculations

a. The objective of a PSHA is to calculate the probability that a selected site ground motion parameter will be exceeded in a specified period of exposure. The computations involve numerical integration to determine the contribution of each source zone to the overall probability of exceedance at the site. The time period for computations is assumed to be one year for the remainder of this discussion.

b. Several computer programs have been developed to perform PSHA. Notably are McGuire (1976, 1978), Chiang et al. (1984), and Bender and Perkins (1987). The computer program RISK by McGuire (1976) has been adapted at WES for PC use and is available as WESRISK (Sykora and Wallace 1993). Some programs, such as FRISK (McGuire 1978), are specifically designed to analyze fault sources and incorporate relationships between magnitude and fault rupture lengths in the hazard computations.

c. Although there are a number of mathematical models for simulating the occurrence of earthquakes in

Table D-1
Parameters in the Predictive Equations of Joyner and Boore (1988) for the Larger of Two Horizontal Components of Pseudovelocity Response (cm/s) at 5 Percent Damping and of Peak Acceleration (g) and Velocity (cm/s) for Stiff Soil Conditions

Period(s)	a	b	c	h	d	k	s	V_{so}*	e	$\sigma_{\log y}$
0.1	2.24	0.30	-0.09	10.6	-1.0	-0.0067	-0.06			0.27
0.15	2.46	0.34	-0.10	10.3	-1.0	-0.0063	-0.05			0.27
0.2	2.54	0.37	-0.11	9.3	-1.0	-0.0061	-0.03			0.27
0.3	2.56	0.43	-0.12	7.0	-1.0	-0.0057	-0.04	650	-0.20	0.27
0.4	2.54	0.49	-0.13	5.7	-1.0	-0.0055	0.09	870	-0.26	0.30
0.5	2.53	0.53	-0.14	5.2	-1.0	-0.0053	0.12	1,050	-0.30	0.32
0.75	2.46	0.61	-0.15	4.7	-1.0	-0.0049	0.19	1,410	-0.39	0.35
1.0	2.41	0.66	-0.16	4.6	-1.0	-0.0044	0.24	1,580	-0.45	0.35
1.5	2.32	0.71	-0.17	4.6	-1.0	-0.0034	0.30	1,780	-0.53	0.35
2.0	2.26	0.75	-0.18	4.6	-1.0	-0.0025	0.32	1,820	-0.59	0.35
3.0	2.17	0.78	-0.19	4.6	-1.0	0	0.29	1,620	-0.67	0.35
4.0	2.10	0.80	-0.20	4.6	-0.98	0.0	0.24	1,320	-0.73	0.35

* V_{so} in m/sec.

time, most PSHA adopt a Poisson process, as originally proposed by Cornell (1968). The following assumptions are inherent with a Poisson model:

(1) The earthquakes are spatially independent.

(2) The earthquakes are temporally independent.

(3) The probability that two seismic events will take place at the same location at the same time approaches zero.

Although these assumptions are not fully consistent with our current understanding of earthquake occurrence, they greatly simplify the mathematical model and may be sufficient to describe the occurrence of moderate to small earthquakes.

d. The annual probability of exceedance, P_a, is the probability that at least one earthquake occurs in any of the seismic source zones that causes the ground motion parameter of interest, A, to exceed a specified level, a, within a time period of one year. From the Poisson probability model, the probability of exceedance is:

$$\begin{aligned} P_a &= P\ (A > a, \text{ at least once in } t = 1 \text{ year}) \\ &= 1 \exp\ (-\ \lambda(a)) \end{aligned} \tag{D-5}$$

where $\lambda(a)$ is the annual number of earthquake events (from any source) that cause A to exceed a. The return period $T_r(a)$ of an event causing A to exceed a is defined as the reciprocal of the annual probability of exceedance given by Equation D-5:

$$T_r(a) = \frac{1}{1-e^{-\lambda(a)}} \tag{D-6}$$

The recurrence interval, $T_a(a)$, also referred to as the interarrival time, is the average length of time between events that cause A to exceed a. As Equation D-7 shows, $T_a(a)$ is defined as the reciprocal of $\lambda(a)$:

$$T_a(a) = \frac{1}{\lambda(a)} \tag{D-7}$$

The values of $T_r(a)$ and $T_a(a)$ will be nearly equal if $\lambda(a)$ is less than 0.1.

e. To calculate the probability P_n that A exceeds a at least once in a project lifetime of n years, use Equation D-8:

$$\begin{aligned} P_n &= P\ (A > a, \text{ at least once in } n \text{ years}) \\ &= 1 - e^{-\lambda(a)n} \end{aligned} \tag{D-8}$$

Alternatively, P_n can be calculated with Equation D-9:

$$P_n = 1 - (1 - P_a)^n \tag{D-9}$$

f. The concept of recurrence interval is often misinterpreted to mean that the event associated with T_a is certain to occur within the time period of T_a years. The actual probability that an event occurs within a period of time equal to the recurrence interval is only 0.63, not 1.0. This is shown by setting $n = T_a(a)$ in Equation D-8:

$$P\ (A \geq a \text{ at least once, } t = T_a\ (a)) \\ = 1 - e^{-\lambda(a)\ (1/\lambda(a))} = 0.63 \tag{D-10}$$

g. Examples of required input and program output are contained in the user manuals for the various available computer programs, in particular WESRISK.

Appendix E Glossary

Accelerogram
The record from an accelerometer presenting acceleration as a function of time.

B-Value, b-line
The rate at which earthquakes of different sizes occur in an area is assumed to follow the Gutenberg-Richter equation:

$$\log N = a - bM$$

where

N = the number of earthquakes within the source area having either a magnitude equal to M (noncumulative) or equal to M plus all smaller magnitude earthquakes (cumulative). Intensity at the point of origin (I_o) can be substituted for M.

a = a value for the overall occurrence rate in the source area.

b = a value controlled by the distribution of events between the magnitude levels.

The relationship plots as a straight line on semilog paper, and it is usually developed by fitting the line to available earthquake records including microearthquakes. The line is extrapolated to indicate time intervals for recurrence of large earthquakes for which data are not available.

Critical structure
A structure for which the consequences of failure are intolerable.

Duration of strong ground motion
The length of time during which ground motion at a site exceeds a designated threshold of severity.

Dynamic analysis
Refers to an analysis where an earthquake base acceleration is numerically propagated through an idealized structure and/or earth mass to determine the response accelerations of points within the structure or earth mass. Responses are functions of the characteristic modes of vibration of elements of the structure and/or points within the mass. The response accelerations determine the magnitudes of earthquake forces that may produce instabilities. The stability analysis of soil mass should use resisting shear strengths that are reduced in proportion to the pore pressure buildup during shaking.

Earthquake
A vibration in the earth produced by elastic rebound of a stressed rock mass following rupture of the rock mass. Note: The following definitions are for specific earthquake terms. The usages are highly specialized, often redundant, sometimes limited to requirements for special purposes, and not always felicitous. The "recommended definitions" are suitable for general use.

Maximum possible earthquake. The largest earthquake that can be postulated to occur. Conceptual only. Probable magnitude 8.7 to 9.5.

Maximum credible earthquake (MCE).

RECOMMENDED DEFINITION: The largest earthquake that can be reasonably expected to occur.

The earthquake that would cause the most severe vibratory ground motion capable of being produced at the site under the currently known tectonic framework. It is a rational and believable event which can be supported by all known geological and seismologic data. The MCE is determined by judgment based on the maximum earthquake that a tectonic region can produce, considering the geologic evidence of past movement and the recorded seismic history of the area. (Bureau of Reclamation: First Interagency Working Group, September 1978).

The earthquake(s) associated with specific seismotectonic structures, source areas, or provinces that would cause the most severe vibratory ground motion or foundation dislocation capable of being produced at the site under the currently known tectonic framework. It is determined by judgment based on all known regional and local geological and seismological data. (Corps of Engineers: ETL 1110-2-301, 29 April 1983).

Maximum expectable earthquake. The largest earthquake that can be reasonably expected to occur. (United States Geological Survey. Same as *Maximum credible earthquake.*)

Maximum probable earthquake. The worst historic earthquake. Alternatively it is (a) the 100-year recurrence earthquake, or (b) the maximum earthquake that may occur during the life of the structure at a specified, probabilistic level of occurrence.

Floating earthquake. An earthquake of a given size that can be conceived to occur anywhere within a specified area (seismotectonic zone).

Safe shutdown earthquake (SSE). That earthquake which is based upon an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake which produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional. (Nuclear Regulatory Commission: Title 10, Chapter 1, Part 100, 30 April 1975. Same as Maximum credible earthquake.)

Design basis earthquake (DBE). Same as *Maximum credible earthquake, Maximum expectable earthquake,* or *Safe shutdown earthquake.*

Design earthquake. The level of ground motion at the site of a structure selected as the basis for an engineering analysis. Selection of the design earthquake may take many factors into account, including: observed local earthquake frequency and intensity, the importance and life expectancy of the structure, and hazard to life and property.

Investment protection earthquake. Same as *Operating basis earthquake.* Applies to installations where sensitive equipment can be shut down in microseconds. Facility remains functional; damage can be repaired with small effort. (DuPont, Bechtel.)

Operating basis earthquake (OBE).

That earthquake which, considering the regional and local geology and seismology and specific characteristics of local subsurface material, could reasonably be expected to affect the structure during its operating life. (Nuclear Regulatory Commission: Title 10, Chapter 1, Part 100, 30 April 1975.)

The earthquake that could occur several times during the life of a structure. The recurrence interval for this earthquake is frequently established as 25 years. The magnitude of the OBE is primarily determined from magnitude versus frequency of occurrence curves that are developed using historically recorded data.

The earthquake(s) for which the structure is designed to resist and remain operational. It may be determined on a probabilistic basis considering the regional and local geology and seismology and reflects the level of earthquake protection desired for operational or economic reasons. The OBE is usually taken as the earthquake producing the maximum motions at the site once in 100 years (recurrence interval). (Corps of Engineers: ETL 1110-2-301, 29 April 1983.)

RECOMMENDED DEFINITION: The earthquake for which the structure is designed to remain operational. Its selection is an engineering determination based on a selected acceptable probability or other estimation that this earthquake can happen during the life of a structure. An installation should remain functional, and damage be readily repairable from an earthquake motion not exceeding the OBE.

Epicenter

The point on the earth's surface vertically above the point where the initial earthquake ground motion originates.

Fault

A fracture or fracture zone in the earth along which there has been displacement of the two sides relative to one another.

Active fault.

Relative displacement during the last 100,000 years, based on direct evidence such as surface rupture, fault creep, and cut or displaced deposits; or on indirect evidence such as sag ponds, stream offsets, scarps, and groundwater anomalies having a direct relationship with a known fault trace. The presence of earthquake epicenters which have a geometric arrangement demonstrating a direct relationship to a fault could indicate the fault is active. (Bureau of Reclamation: First Interagency Working Group, September 1978.)

Instrumentally recorded microearthquakes, creep, or geomorphic evidence of movement.

RECOMMENDED DEFINITION: A fault, which has moved during the recent geologic past (Quaternary) and, thus, may move again. It may or may not generate earthquakes. (Corps of Engineers: ETL 1110-2-301, 23 April 1983.)

Inactive fault. No evidence of geologically recent movement. No interpreted ability to cause earthquakes.

Capable fault.

RECOMMENDED DEFINITION: An active fault that is judged capable of generating felt earthquakes.

A "capable fault" is a fault which has exhibited one or more of the following characteristics: (a) movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years; (b) macroseismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault; (c) a structural relationship to another capable fault such that movement on one could be reasonably expected to be accompanied by movement on the other. In some cases, the geologic evidence of past activity at or near the ground surface along a particular fault may be obscured at a particular site. This might occur, for example, at a site having a deep overburden. For these cases, evidence may exist elsewhere along the fault from which an evaluation of its characteristics in the vicinity of the site can be reasonably based. Such evidence shall be used in determining whether the fault is a capable fault within this definition. Structural association of a fault with geologic structural features which are geologically old (at least pre-Quaternary) such as many of those found in the Eastern region of the United States shall, in the absence of conflicting evidence, demonstrate that the fault is not a capable fault. (Nuclear Regulatory Commission: Title 10, Chapter 1, Part 100, 30 April 1975.)

A capable fault is one that is considered to have the potential for generating an earthquake. It is defined as a fault that can be shown to exhibit one or more of the following characteristics: (a) movement at or near the ground surface at least once within the past 35,000 years; (b) macroseismicity (3.5 magnitude or greater) instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault; (c) a structural relationship to a capable fault such that movement on one fault could be reasonably expected to cause movement on the other; (d) established patterns of microseismicity that define a fault and historic macroseismicity that can reasonably be associated with that fault. (Corps of Engineers: ETL 1110-2-301, 29 April 1983.)

A capable fault is any fault that displaces surficial layers of gravel or cuts the base of surficial gravels or alluvium or glacial veneer.

Dead fault. Same as *Inactive fault.*

Fault-plane solution
Slip along a fault produces a quadrantal radiation pattern of seismic waves that reflect dilatational and compressional forces. The waves can be analyzed as four lobes which are divided by two planes, one of which has the orientation of the fault plane, the other has the slip vector as its normal. The distinction between the fault plane and the auxiliary plane cannot be made from the focal mechanism itself but must be decided from a comparison with the local geology.

Focal mechanism
Same as fault-plane solution.

Focus
The location within the earth where the slip responsible for an earthquake was initiated. Also called the *Hypocenter* of an earthquake.

Free field
An idealized area in which earthquake motions are not influenced by topography, man-made structures, or other local discontinuities or irregularities.

Ground motion
Numerical values quantifying vibratory ground motion, such as particle acceleration, velocity, displacement, frequency content, predominant period, spectral values, intensity, and duration.

Hard site
A site where shear wave velocities in the base stratum are greater than 400 m/sec and overlying soft layers with smaller shear wave velocities are less than or equal to 15 m in thickness. (See Soft site.)

Hotspot
An area where the seismicity is anomalously high compared with a surrounding region.

Hypocenter
Same as Focus.

Intensity
A subjective numerical index describing the effects of an earthquake on humans, on their structures, and on the earth's surface at a particular place. The number is rated on the basis of an earthquake intensity scale. The scale in common use in the United State today is the Modified Mercalli (MM) Intensity Scale of 1931 with intensities indicated by Roman numerals from I to XII. In general, for a given earthquake, intensity will decrease with distance from the epicenter. The following is an abridgement of the scale.

a. Not felt except by a very few under especially favorable conditions.

b. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

c. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing of truck. Duration can be estimated.

d. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably.

e. Felt by nearly everyone; many awakened. Some dishes, windows, and other fragile items broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

f. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

g. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving automobiles.

h. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Great damage in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving automobiles disturbed.

i. Damage considerable in specially designed structures; well-designed frame structures thrown out-of-plumb; damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

j. Some well-built wooden structures destroyed; most masonry and frame structures destroyed. Ground badly cracked. Railroad rails bent. Many landslides on riverbanks and steep slopes. Shifted sand and mud. Water splashed over banks of rivers and lakes.

k. Few structures remain standing. Unreinforced masonry structures are nearly totally destroyed. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Railroad rails bent greatly.

l. Damage total. Waves apparently seen on ground surfaces. Lines of sight and level appear visually distorted. Objects thrown upward into the air.

Liquefaction
The loss of strength of a saturated cohesionless material subjected to shear stress large enough to cause relative movement of the soil grains into a denser configuration under conditions where the pore-water cannot readily escape, with the result that the pore pressure increases and effective intergranular pressure decreases.

Magnitude
A measure of the size of an earthquake related to the total strain energy released.

Body wave magnitude (m_b). The m_b magnitude is measured as the common logarithm of displacement amplitude in micrometers of the P-wave with period near one second. Developed to measure the magnitude of deep focus earthquakes, which do not ordinarily set up detectable surface waves with long periods. Magnitudes can be assigned from any suitable instrument whose constants are known. The body waves can be measured from either the first few cycles of the compression waves (m_b) or the 1-second period shear waves (m_{blg}).

Local magnitude (M_L). The original magnitude definition by Richter. The magnitude of an earthquake measured as the common logarithm of the displacement amplitude, in microns, defined by a standard Wood-Anderson seismograph located on firm ground 100 km from the epicenter and having a magnification of 2800, a natural period of 0.8 second, and a damping coefficient of 80 percent. The definition itself applies strictly only to earthquakes having focal depths smaller than about 30 km. Empirical charts and tables are available to correct to an epicentral distance of 100 km for other types of seismographs and for various conditions of the ground. The correction charts are suitable up to epicentral distances of about 600 km. The correction charts are site dependent and have to be developed for each recording site.

Surface wave magnitude (M_s). This magnitude is measured as the common logarithm of the resultant of the maximum mutually perpendicular horizontal displacement amplitudes, in microns, of the 20-second period surface waves. The scale was developed to measure the magnitude of shallow focus earthquakes at relatively long distances. Magnitudes can be assigned from any suitable instrument whose constants are known.

Richter magnitude (M). Richter magnitude is a general usage that is usually M_L up to 5.9, M_S for 5.9 to about 8.0, and M_w up to 8.3.

Seismic moment (M_o). Seismic moment is an indirect measure of earthquake energy.

$$M_o = G\ A\ D$$

where

G = rigidity modulus

A = area of fault movement

D = average static displacement

The values are in dyne centimeter units.

Seismic moment scale (M_w). Defines magnitude based on the seismic moment:

$$M_w = 2/3 \log M_o - 10.7$$

Modal analysis
A method of evaluating earthquake effects in which the responses of a structure in its normal modes are determined separately, and then superimposed to determine the total response. Its applicability is limited to linearly elastic systems on which all applied forces have the same time dependency. It is a form of dynamic analysis.

Particle acceleration
The time rate of change of particle velocity during earthquake shaking.

Particle displacement
The difference between the initial position of a particle and any later temporary position during earthquake shaking.

Particle velocity
The time rate of change of particle displacement during earthquake shaking.

Power spectral density (PSD)
A measure of the ground-motion power or energy per unit time as a function of frequency. Usually, estimates of the PSD are obtained from the square amplitudes of the Fourier transform, or the squared Fourier amplitude spectrum.

Predominant period
The period(s) at which maximum spectral energy is concentrated.

Pseudostatic analysis
An analysis in which horizontal and vertical forces are taken as equivalent to selected horizontal and vertical seismic coefficients multiplied by the weight of a structure or portion of a structure to be analyzed. The intent is to approximate the dynamic effects of earthquake shaking on the structure by using the forces in conventional static analyses.

Response spectrum
The maximum values of acceleration, velocity, or displacement experienced by single-degree-of-freedom systems spanning a selected range of natural periods when subjected to a given time history of earthquake ground motion. The spectrum of maximum response values is expressed as a function of the natural period of single-degree-of-freedom systems for a given damping. The response spectrum acceleration, velocity, and displacement values may be calculated from each other as a function of the natural period by assuming that the motions are harmonic and undamped. When calculated in this manner, these are sometimes referred to as pseudo-acceleration, pseudo-velocity, or pseudo-displacement response spectrum values.

Root mean square acceleration (A_{rms})
The average resultant acceleration during the strong motions of accelerograms recording motion in two orthogonal directions. It is the square root of the sum of the square of the accelerations in the two directions. The A_{rms} can be calculated in the time or frequency domain.

Saturation
The point where ground acceleration, velocity, and displacement reach upper-limit values determined by local properties of earth and rock density, strength, and stiffness. The values will not increase even though the earthquake energy release increases.

Scaling
An adjustment to a given earthquake time history or response spectrum where the amplitude of acceleration, velocity, or displacement is increased or decreased, usually without change to the frequency content of the earthquake record, to model the effects of earthquakes of greater or lesser magnitude than the prototype event.

Seismic hazard
The potential damaging effects of an earthquake.

Seismic risk
The statistical probability that an earthquake equal to or exceeding a given size will occur during a given time interval in an area of specified size.

Seismic zone
A geographic area characterized by a combination of geology and/or seismic history in which a given earthquake may occur anywhere.

Soft site
A site underlain by a surface layer 16 or more meters thick in which shear wave velocities are less than 400 m/sec. (See Hard site.)

Structure seismic coefficient (C_s)
Factor in the usual building code base formula that reflects the structure's natural frequency of vibration, which determines the structures's response and degree of resonance with the frequency and energy distribution of the ground-based acceleration.

Subduction zone
A zone between a sinking plate and an overriding plate.

Transform fault
A strike-slip fault along which some plates or portions of plates slide past each other.

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Earthquake ground motions for major engineering projects are based on a thorough evaluation of geologic hazards to identify earthquake sources and to estimate the earthquake potential of each. Earthquake ground motions are assigned to the sources by either deterministic or probabilistic procedures.

A deterministic evaluation takes the maximum credible earthquakes from each source and attenuates their motions to the site. Accelerograms and/or response spectra are assigned to represent analogous earthquake excitations at the site. The objective is to design against any reasonable eventuality, regardless of time, because there is no way to know when the earthquake may or may not happen during the design lifetime of a critical structure.

A probabilistic evaluation includes the element of time in the assessment of an earthquake threat. Simple probability is based on projections of b-values. More complex probabilities involve adjustments to the b-values. None of these is reliable.

The deterministic method is used for assigning earthquake ground motions for critical structures in seismically active areas. Simple probability, based on seismic hazard maps, can be used for non-critical structures or for areas of low seismic threat.

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